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A practical voiceband television system design.

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THESIS

A PRACTICAL VOICEBAND TELEVISION SYSTEM DESIGN

by

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September 1973

A Practical Voiceband Television System Design

by

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ABSTRACT

A need exists to send television on channels of limited bandwidth, particularly 3 kHz. Successive images must have adequate picture content yet be frequent enough to give the appearance of motion. A new coding scheme was devised to meet this need for video data compression.

A 2400 baud system was designed and built. A hierarchy of transmission modes is used which allows the transmitter to choose the most efficient of 3 modes to send a line. One mode uses a variable-length Instantaneously Uniquely Decipherable code optimized for the statistics of some typical expected pictures. The picture size is 64 by 64 elements, each with 4 luminance levels. The transmitter has a stored line (129 bits) and a two-dimension model to predict the following line. After comparing the prediction to a fresh line the deviations from the prediction are sent. Then the receiver uses the same model to update a similar stored line to be displayed. Frame duration can range from .13 to 3.54 seconds as determined by the actual picture.

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I. PROBLEM DESCRIPTION

There is demand for a practical system that can transmit acceptable television pictures on a restricted bandwidth. There is a special need to do this on a voiceband (3 kilohertz wide) channel because most existing transmission systems use this as a standard channel. Such a television system is particularly needed by the military where pictures from unmanned platforms exposed to personnel dangers would be of great value.

In virtually every picture there is a strong correlation (in brightness and color) between any given spot and its neighbor spots. Most spots (picture elements) are thus predictable in both light level and color from their neighboring spots. The boundary of an object in the picture determines a change in the image. Theoretically, a television system needs only to send the changes (the corrections to the predictions of the next spot) at such boundaries. Existing commerçial television systems are grossly inefficient in the transmission of information because each spot is separately transmitted. No prediction scheme is attempted. A better scheme reported by Beltrami [2] used on spot to predict the value for the next adjacent spot and the transmitter transmitted only the changes from the prediction. The receiver similarly made the same prediction and updated the prediction based on the information received. This scheme was a one-dimension prediction scheme. It proved

that a more efficient system can be built which includes transmitters and receivers with some memory. Furthermore, the larger the memory, the more efficient the scheme can be. The next system improvement, suggested by Rice and Plaunt [10] is to provide for a two-dimensional prediction scheme using a full line of memory.

In more general terms, the problem was described by Shannon [11]. He defined a measure of information transmission as the uncertainty of a given data point. He called the measure "entropy." The uncertainty in television is determined by both prejudice (the overall statistical properties of the picture) and history (the values of recently transmitted data for adjacent spots).

The problem is to devise and test a scheme that increases the entropy of the transmitted data. This increases the information rate transmitted in a given signal bandwidth (i.e. for a given binary bit transmission rate).

II. APPROACHES

There are two complementary general approaches to enhancing the information rate of a band-limited television scheme.

The first approach assumes that the human eye and brain combination is the end user. The eye-brain system is non-linear in two ways: it has a propensity for edges (a sort of differentiating effect) and it has a logarithmic intensity level response. This combination extracts only certain kinds of information from a scene which allows the viewer to re-construct it in his mind and then to experience seeing it [6]. A television system needs only to send the information which is sufficient to excite a valid image reconstruction in the viewer's mind. First of all, one can use the fact that the eye-brain combination is more responsive to edges than to single points or to uniform regions. In addition, it is known that eye response to brightness is logarithmic [3]. Therefore, a system need not quantify and transmit evenly spaced picture element luminance levels. More value is gained in concentrating the distinguishing levels in the darker regions and spreading them in the bright region.

The second approach is to code picture elements in such a way as to maximize the entropy (an uncertainty measure) per transmitted bit. A great deal of work has been done in this field [1]. It is not enough in television, however, to send just the value of a new or changed picture element.

Address information is also required. For example, in ordinary television, every picture element is assumed to be the next element to the right (or occasionally the beginning of a new line). Other schemes can give an absolute element address in terms of rows and columns, or a relative address in terms of the length, in some direction, from the element previously addressed to the current one.

Redundant information transmission should be reduced as much as possible to conserve bandwidth. The amount of possible reduction is dependent on the size of the memory. The more data that is stored in a transmitter and in a receiver, then the more sophisticated a transmission coding scheme may be used. The dropping cost of memory now allows development of better systems for some applications. A standard commercial television set is a worst case since it has no memory. Consequently, each picture element in each line and each line in each frame and each frame in time is laboriously and wastefully transmitted.

The amount of redundancy in a television picture varies greatly and is dependent on whether the subject has great detail and also dependent on the relative motion with the camera. (Also it depends on the quantization scheme and the method of scan although these are strictly speaking functions of the system and not of the picture alone).

It has been pointed out by both Campbell [3] and Ingerson [5] that in a picture, the element to element correlation is strong, but that line to line correlation is

stronger and frame to frame correlation is strongest. Ingerson [5] says that a non-panning picture has frame to frame correlation usually well above 90%. Campbell [3] says it is close to 95% for the average picture. This correlation figure is the probability that each dot will be of the same brightness level (within some specified tolerance) as the corresponding dot of the previous frame. Line to line correlation is estimated to average 90%. This is the probability that a dot is predictable from the corresponding dot of the preceding line and at least one adjacent dot of the same line. Other surrounding dots can be used in addition. Element to element correlation is estimated at about 80%. Beltrami and Mosca [2] built and operated a system with a one bit memory that demonstrated over 90% correlation element to element for two levels (black and white) on graphic material, but this is a special case.

The more memory a receiver has the less information to predict a given data point, hence the less information must be transmitted to correct the prediction. In order for a receiver to store a whole frame, a great deal of storage is required. For example, in binary form every bit of each quantized picture element is stored separately. If a picture has 8 brightness levels, then each picture element uses at least 3 bits of storage. With 400 elements per line and 300 lines per frame, a frame would require 360,000 bits of storage. At the present time, 1973, the hardware for this amount of storage is still relatively expensive. For

example, at 3¢/bit such a frame storage would cost over $10,000 for each the transmitter and receiver terminals. This cost is high partly because both a good prediction scheme and an efficient coding scheme require random access with fairly short retrieval times. Otherwise the system would not be able to keep up with the movement in the picture.

However, someday when memories are cheaper, it will be economical for some applications to store two or more frames of data. The a scheme could be used that preserves linear motion of an object in the picture. Such a system for example, could project the movement of a picture subject (say a car) across a bacground (say the desert). Only the freshly exposed background (say a cactus that had been hidden beyond the car) would need to be sent. This system would further improve the transmission efficiency, but it is well beyond the scope of this thesis.

For applications such as guiding a missile to its target from great distances, it is currently feasible to implement in hardware a system using line to line correlation in the transmitter to determine what to send, and one line of picture stored in the receiver. This provides sufficient memory for a two-dimension prediction scheme. It normally requires two lines of storage in transmitter since, if a Vidicon pickup is used, it must read out at a high but uniform rate. Then the correlation is performed at a lower speed as transmission occurs. For comparison with the

previous example given for frame storage, one 400 element line with 8 brightness levels would require only 1200 bits of memory.

One further observation: a trivial case of information reduction for a control application would occur if one agreed to slow the frame rate. This is because the effect of apparent motion within a picture is lost and one really ends up with only a fast facsimile system. The tradeoff of speed for picture resolution cannot reduce the product of frame-time and bandwidth, hence information transmission efficiency is not affected.

III. SYSTEM STANDARDS

The setting of engineering design standards for any given television system is at best a subjective compromise based on the needed applications. A voiceband video system would have utility in aiding control of missiles all the way to a distant target. Because High Frequency (3-30 MHz) transmission could be used, the target could be well over the horizon beyond the line-of-sight. Such a missile's video could be stored on an audio tape recorder without modification, hence, strike evaluation data would be cheaply available. Another application would be to control a drone aircraft into battle without risking a pilot. Another application is to send television on regular commercial long line, cable, microwave and satellite systems (The Bell Systems has been developing a high resolution "Phonovision" system with 50 kHz bandwidth for 10 years, but it is not yet marketable) [12]. Other applications include any requirements for video information from an environment hostile to man such as from under the sea or in high temperature areas. The system in this thesis is cheap enough ($400 worth of components) that it is suited for application where the camera and transmitter are expendable or quasi-expendable. It should be compatible with all existing military, commercial and amateur voice communication systems, including enciphered voice channels.

A. PICTURE TRANSMISSION MODES

The first part of the problem involves how to code the picture for transmission.

The Secure Image Transmission System (SITS) was built by Philco-Ford as a high resolution fast facsimile transmission system [9]. The system codes each picture element at 2, 4, 8 or 16 brightness levels at the operator's option. The data is "compressed" by the vidicoder and then transmitted at 2400 baud. The system was installed in June 1972 on the flagship of Commander, U.S. Seventh Fleet, USS OKLAHOMA CITY. The mate was installed in July 1972 at Commander-in-Chief, U.S. Pacific Fleet Headquarters. The most interesting component, the vidicoder, was designed in 1967, only recently built, and now under Navy evaluation.

The vidicoder uses "Run Length Coding" which encodes the distance to the next change. It stores one line at a time. An example of its operation follows: After quantizing at one bit per element (two level; black, white), the distance to the next level transition is coded up to a distance of 8 picture elements. This generates a 3 digit binary number. Transmitted then, is a sequence of 3 digit numbers representing the line of the picture. For example: a binary sequence ..., 101, 000, 010, 111, ... (octal .. 5027 ..) means that from the last change, one counts the next 5 elements in one state and changes the state, say from white to black of the element which follows. Then the very next element is changed back to white. Then the next two

elements are also in the white state, but the third one is changed to black. Then the vidicoder counts past 7 elements, setting them all at the black state and finally, without changing the state of the 8th element, it proceeds to a fresh count. Twelve bits are thus transmitted to control 18 bits of picture. In the two level mode, a high resolution picture such as a status board, a weather map or an electrocardiogram is transmitted in about 1 minute, the time depending partly on picture complexity.

When the operator chooses to transmit a 16 level picture, each element is coded into a 4 bit code where the ith element is represented by X_{1i}, X_{2i}, X_{3i}, and X_{4i}. Then as soon as one line is stored by columns, the control section clocks out the bits by rows X_{11}, X_{12}, ... X_{1i}, ... X_{1n}, X_{21}, X_{22}, ... X_{2i}, ... X_{2n}, X_{31}, X_{32}, ... Using this scheme, some rows of bits are very "busy" and probably no economy is realized in that region. Other rows of bits (say the most significant rows) don't encounter as many transitions and hence have data compression approaching 5/8. It takes the SITS about 4 to 4 1/2 minutes to transmit a typical reconnaissance photo. The average data compression actually achieved in the field has ranged between 30% and 40% with subjects of typical military interest. The SITS interfaces with standard narrow-band voice cipher equipment at 2400 baud.

Even though the SITS is the latest operational system, it is only a blunderbus approach to the data compression problem. Since the statistics of the lines in a given picture vary so

widely, it would be better if a coding scheme were available for several sets of statistics. Then a coder mechanism could: (a) choose the best code for a convenient batch of data, (b) identify the code chosen to the receiver, (c) code that batch of data and send it and (d) then have the receiver set up to receive the identity of the appropriate code for the next batch. A hierarchy of signals is thus required with the choice of code at the upper echelon and the actual coding at the lower echelon.

To demonstrate this hierarchy technique this thesis project uses 3 modes: the Sequential Mode, the Repeat Mode and the Jump Mode.

1. Sequential Mode

At the beginning of each transmission, and whenever there are many changes from the previous line, it is necessary that every picture element in a line be transmitted. Rather than explicitly sending the address of every dot in this line, there is a Sequential Mode. This mode is analogous to commercial television. The address information in this mode is that each dot is immediately to the right of the previous one, thus specific addresses are not required. As later described, this mode will be selected for each line which has more than about 35% of the picture elements (specifically more than 31 bits) different from the prediction based on neighboring elements of the previous line and the same line.

2. Repeat Mode

Whenever a new line is the same or nearly the same as its prediction, the transmitter will select the Repeat Mode. This mode will be chosen when the maximum number of differing corresponding line elements is less than about 5% (specifically, less than 4 bits). In this mode, there will be no memory update, the line will simply be repeated by sending a line trigger signal. It is accepted that some small error can be accumulated, but the error will not grow beyond 3 bits since the line store in the transmitter memory is not updated.

3. Jump Mode

The third mode of system operation is the Jump Mode. This mode is selected whenever more than 3 bits but less than 32 bits of the previous line elements need updating for the current line. The transmitter will transmit the number of picture elements up to the next different picture element using an Instantaneously Uniquely Decipherable (IUD) code. The code chosen is a Huffman code [1] which is an optimal IUD code. The rationale for and explanation of this type of code follows in Section IV.A.2 of this thesis.

The salient difference between the SITS Run Length Coding and the Jump Mode of this paper is that this one uses an optimal code of variable word length depending on the expected probability of change at a given number of elements after the last change.

B. MODULATION RATE

There is presently a voiceband video system which is gaining popularity in the amateur radio community. It is called "Slow-Scan" Television (SSTV) and it takes about 8.3 seconds to transmit a frame [8]. It is a Frequency Modulation system with good noise immunity and it inter-faces with standard single-sindeband voice tranceivers. The picture element brightness is represented by a linear analog voltage. As with commercial facsimile, the frequency standards are 1200 Hz for line (and frame) trigger and continuously from 1500 Hz (representing black) to 2600 Hz (representing white). The modulation index, m, is equal to 1. The amateur community is a very economy-oriented mass market for a better but inexpensive system.

Modern data transmission systems use more of the available bandwidth. Most military high speed data is passed on systems which have an information rate of 2400 bits per second (or 2400 baud). This is the rate chosen for this thesis. This thesis design does not rely, however, on any particular modulation scheme.

C. PICTURE SIZE

The most popular current so-called "standards" for SSTV* are for a picture with about 100 to 120 elements per line

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*The Federal Communications Commission, in order to foster independent development and improvement, has typically and steadfastly refused to allow specific standards to be prematurely set. Their Rules (paragraph 97.61) require only that a SSTV signal must remain within a 3 kHz bandwidth.

and about 120 lines per frame. The aspect ratio is 1/1, thus yielding a square picture.

The design in this thesis however, has good resolution because of its digital nature. Each element is quantized, coded, transmitted, stored and displayed. This precludes smearing as a result of poor pass-band response of the transmission path or of the equipment, except in the display oscilloscope.

Another consideration is the length (and cost) of available data storage devices. One line of storage is available at about $10.00 for 192 bits (about 5¢ per bit).

Another consideration is the fact that the frame repetition rate of SSTV, which is 8.3 seconds, is too slow to give the appearance of motion, thus it is not acceptable as a television to be used in remote control. (It is more properly called fast facsimile.) Therefore, a smaller picture is required.

With these factors in mind, a square picture was chosen with 64 elements per line and 64 lines per frame. The smallest acceptable size must be chosen due to the narrow band.

D. ELEMENT QUANTIZATION

Another overall design consideration involves determining the minimum number of light levels which are acceptable. Of course there are no gray tones whatever with a one-bit (white/black) scheme. For the applications planned, a 3 level scheme would also be inadequate though much better than 2 levels. A 4 level scheme (white/light/dark/black) still does not give

a commercial quality picture. However, the objects in such a picture are readily indentifiable. One objectionable feature of this two-bit scheme is that the gray shadings form distinct contours. The effect of these contours has been investigated by Campbell [3] and by Lippel and Kurland [7]. However, the 4 level quantization mode of a system was witnessed at the SITS installation and judged to provide sufficient quality for the planned applications. Again, because of the very narrow bandwidth, the least number of quantization levels must be chosen than can provide an adequate picture.

E. STANDARDS SUMMARY

There are 3 transmission modes: Sequential, Repeat and Jump. The transmitter selects the best mode for each line. If there are 32 or more new line bits different from the predicted line, the Sequential Mode is used. The transmitter sends a whole line (128 bits) in sequence just as does commercial television. If there are less than 4 bits differing from the prediction, the Repeat Mode is used. The predicted line is displayed immediately at the receiver and the transmitter considers another fresh line. In the case of 4 to 31 bit differences from the predicted line, the Jump Mode uses an optimal code to send the number of bits to jump to make the next correction to the prediction.

A modulation rate of 2400 baud was chosen because it can be passed on voice single-sideband channels and can interface with almost all military data trunks. A picture

size of 64 by 64 elements quantized to 4 levels was picked to allow the frame duration to be kept in the range of from .13 seconds to 3.54 seconds depending on how much each line varies from its prediction. Data compression of over 50% is expected for most pictures with a frame rate of about one per second. The sweep is an asynchronous triggered sweep, hence frames will not have uniform duration. The sweep is from left to right for the elements of a line and the lines from top to bottom. Figure 1 shows a typical actual target view, and Figure 2 shows the same view quantized, processed and reconstructed according to the scheme of this thesis.

Figure 1. Typical Target -- A KASHIN Class DDG.

(Official U.S. Navy photograph)

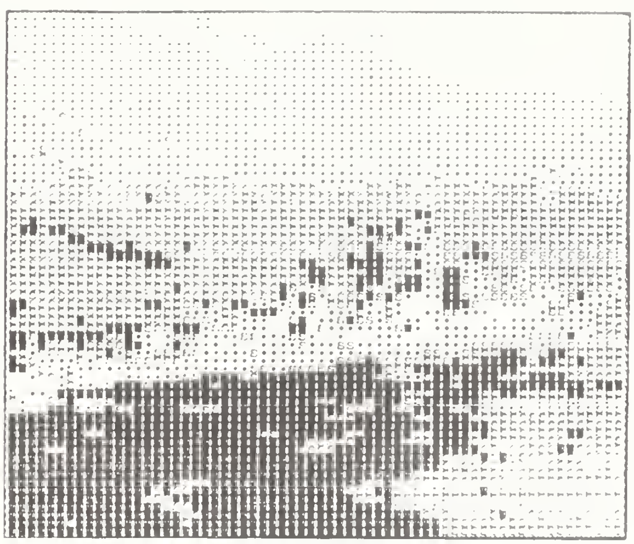


Figure 2. A Quantized Processed Recomposed KASHIN.

IV. DESIGN CRITERIA AND ASSUMPTIONS

A. SYSTEM DESCRIPTION

Once the standards had been chosen, a functional outline block diagram was devised for each the transmitter and the receiver. From these outlines "single line" logic diagrams were developed. From the single line diagrams actual available logic components were chosen and an initial layout was made. This resulted in a system design consisting of 85 Transistor-Transistor-Logic (TTL) chips and some miscellaneous components assembled onto six 5" x 7" circuit boards labelled as follows:

Camera Control Board

Transmitter Storage Board

Transmitter Coding Board

Transmitter Control Board

Receiver Control & Storage Board

Receiver Decoding Board

1. Two-Dimension Spot Prediction

When predicting a spot from one line of storage, a maximum of 4 neighborhood spots can be reasonably used: "above left," "above," "above right" and "alongside." The other spots (picture elements) are not available. See Figure 3.

Figure 3. Neighbor Spots Available For Predictions

The two spots with the most influence, however, are the one "above", A, and the one just "before", B, which is alongside. This thesis uses these two spots to predict the value of the current spot, C. This is an engineering compromise to simplify the circuits. Notice that since the targets of greatest interest are ships and buildings, they have more edges close to vertical than close to horizontal (because of picture aspect). The spot above is therefore slightly favored in the averages which determine the predicted level. Figure 4a shows the best brightness level prediction matrix.

"A" - Spot Above

"B" Spot Before		B	D	L	W
	B	B	D	D	L
	D	B	D	L	L
	L	D	D	L	W
	W	D	L	L	W

"C" Current Spot

Figure 4a. Brightness Prediction Matrix.

The notation for the 4 light levels is "B" for Black, "D" for Dark gray, "L" for Light gray and "W" for White.

There is a well known Gray code, named for its inventor, used first for shaft-position coding. It has the characteristic that, as the position varies, the coded output

never changes more than one of its bits at a time (i.e. the Hamming distance [1] between code words for adjacent positions is always 1). The Gray code is used here to code gray levels so that at a threshold of light levels the code sent is either correct or it is for the immediately adjacent level. The Gray code chosen was arbitrary: 0,1 for Black; 0,0 for Dark; 1,0 for Light; and 1,1 for White. The binary digits are shown in the order coded. The binary equivalent to Figure 4a is shown in Figure 4b. where each spot is coded as x,y.

"B" - Spot Before	"A" - Spot Above: 0,1	0,0	1,0	1,1
0,1	0,1	0,0	0,0	1,0
0,0	0,1	0,0	1,0	1,0
1,0	0,0	0,0	1,0	1,1
1,1	0,0	1,0	1,0	1,1

"C" - Current Spot

Figure 4b. Binary Representation of Prediction Matrix.

At time x, the output of the prediction for C (call it x_C) is given by:

$$x_C = (\overline{x}_A \cdot \overline{y}_A \cdot x_B \cdot y_B) + \{x_A \cdot [y_A + (x_B + \overline{y}_B)]\}$$

This simplifies to an expression using "exclusive or":

$$x_C = x_A \oplus \left[(x_A \oplus x_B) \cdot \overline{y_A} \cdot y_B \right]$$

Figure 5a shows the relationship of the predictor to the line storage.

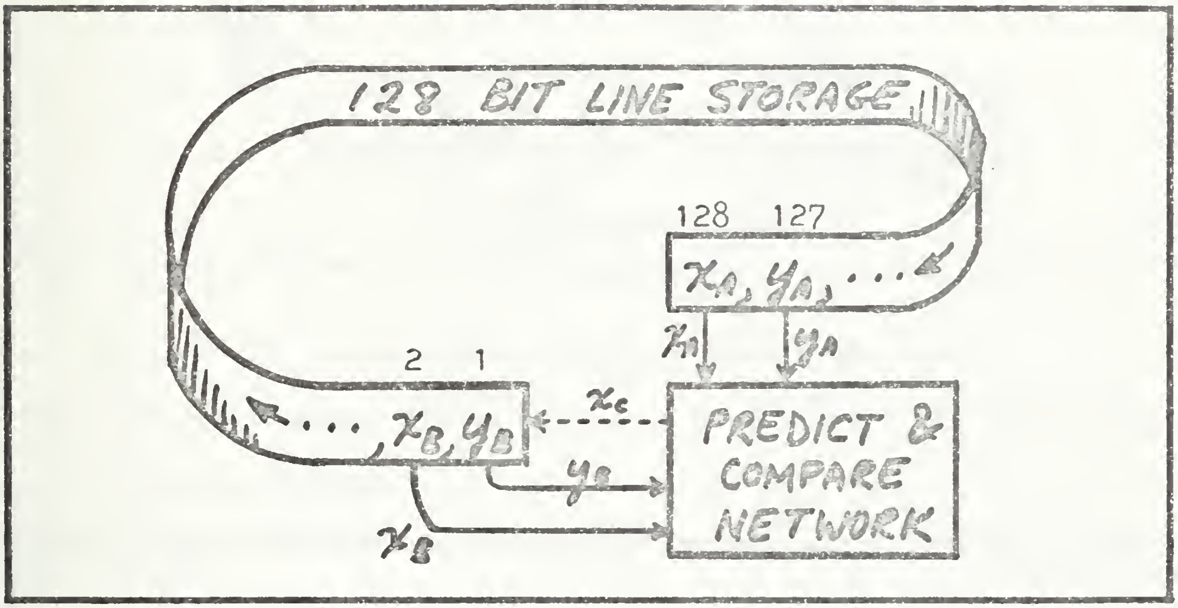


Figure 5a. Predictor Connection at Time "x".

The dotted lines show the direction of data flow at the next clock transition. At time "y", the following logic is implemented:

$$y_C = y_A \cdot \left[(x_A \cdot x_B) + (\overline{x_A} \cdot \overline{x_B}) \right]$$

This simplifies to the expression:

$$y_C = y_A \left[\overline{x_A} \oplus x_B \right].$$

One extra bit of storage is required for the predictor in addition to the 128 bits required for the line itself. This is shown in Figure 5b.

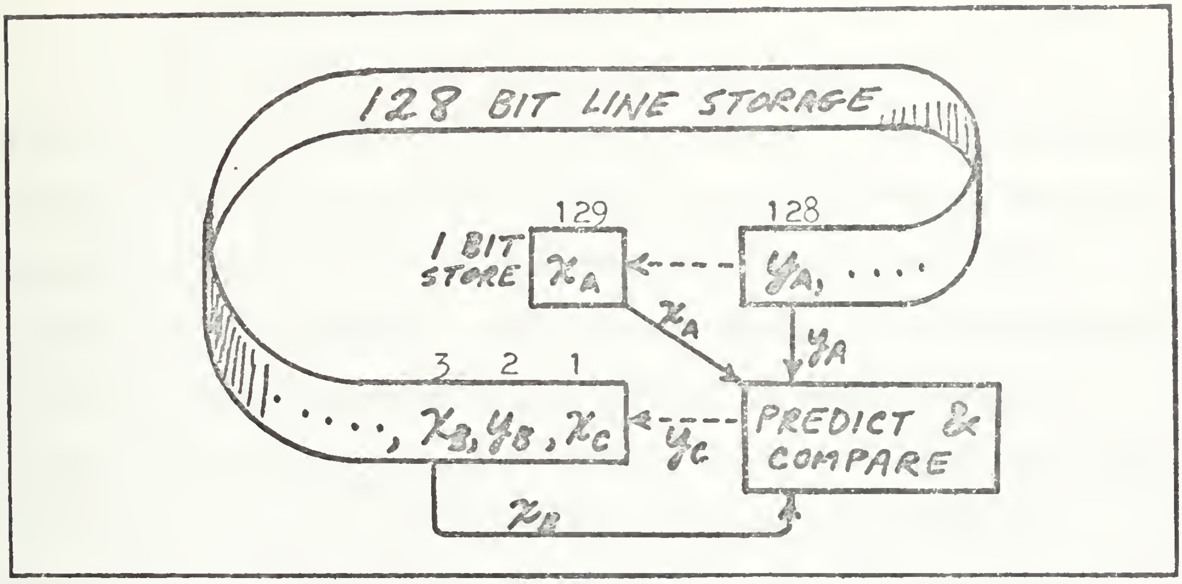


Figure 5b. Predictor Connection at Time "y".

The logic elements which form the two-dimension predictor are shown in Figure 6.

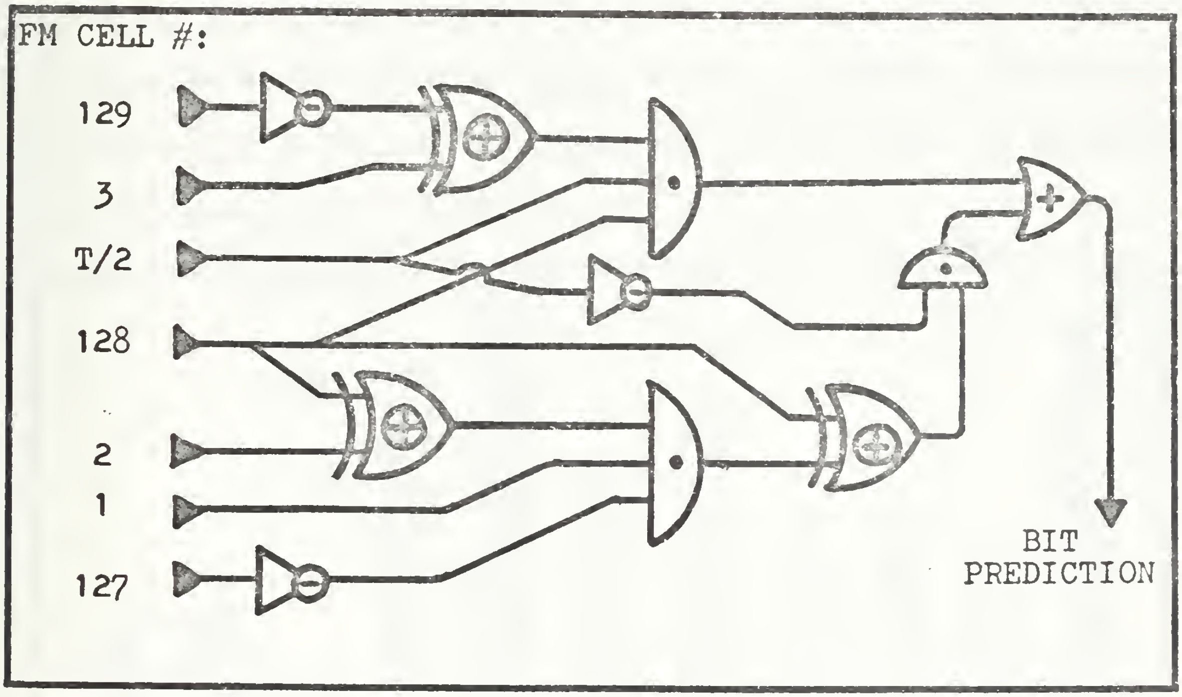


Figure 6. Prediction Logic Network.

Of course, a Read-Only-Memory (ROM) can replace the network shown.

2. A Huffman Optimal Code

The structure of the Jump Mode code, indeed its optimality, is dependent on the knowledge of the conditional probability that a picture element will have the predicted luminance level given the current values of some known neighborhood elements. Other investigators such as Campbell [3] have developed more sophisticated schemes to make a better prediction of a given point, but the scheme here was constrained by the practical economic factors of this application. Since a Gray code for a two-bit gray scale is used, a change from one luminance level to an adjacent one will only involve changing 1 of the 2 quantization bits. Since this is more likely crossing single contours, it is estimated that bits at even numbered distances have a higher correlation with the last change. This judgement and other related factors led to the assignment of expected conditional probabilities shown in Figure 7.

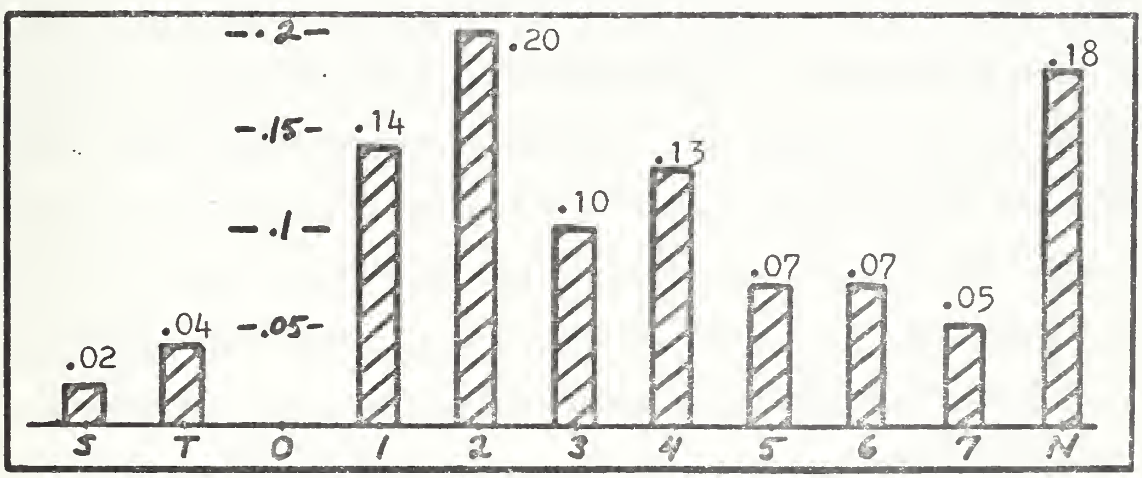
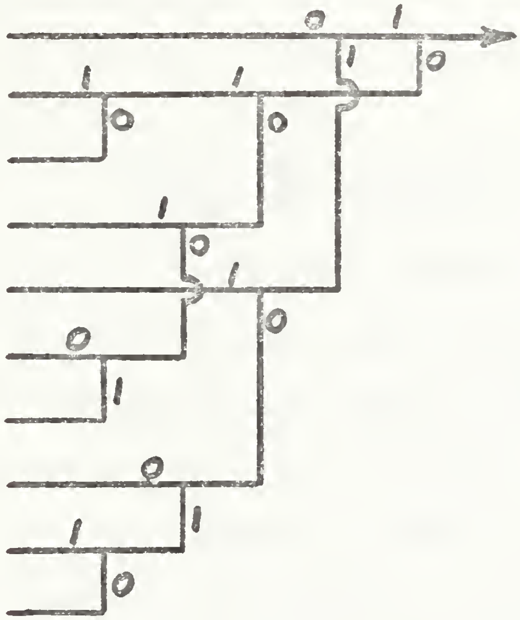


Figure 7. Probability of Predictor Error vs. Distance.

In this figure, event "N" (meaning No change) occurs when we count 7 bits without encountering a change form the prediction. Event "T" occurs when the end of the line, 128 bits, is met since this causes a line trigger to be ordered. Event "S" occurs when the order Sequential is needed.

There is a class of binary codes which are called Uniquely Decipherable [1]. Such a code, unlike the SITS code described in Section III.A., can be picked up anywhere in its interior and be correctly decoded. Within that class is another class of Instantaneously Uniquely Decipherable (IUD) codes. A code of this type has the additional characteristic that no code word is is a prefix to another. In this case, as soon as a code word is completed the receiver can decode it properly with no dependence on the follow-on bit stream. Huffman, while a student of Fano, discovered a procedure using a tree to generate an IUD code. Furthermore, if the events were ordered according to their probability, the code optimizes the information transmission rate. No other code with a 1:1 correspondence of events and code words can yield improvement. Shannon [11] showed that the limit of new information that any code can carry, given the statistics of the events, is the entropy, H. The calculation of entropy, the generation of the Huffman code, the computation of weighted average Huffman code work length, $\overline{n}$, and the determination of the coding efficiency, η, are all shown in Figure 8. The short code words are used for the more frequent events. This is what reduces the average word

p(i)	Huffman Code Tree	w(i)	p·w	$p \cdot \lg\frac{1}{p}$
p(2)=.20		10	.40	.464
p(N)=.18		011	.54	.445
p(1)=.14		010	.42	.397
p(4)=.13		001	.39	.383
p(3)=.10		111	.30	.332
p(6)=.07		0000	.28	.269
p(5)=.07		0001	.28	.269
p(7)=.05		1100	.20	.216
p(T)=.04		11011	.20	.186
p(S)=.02		11010	.10	.113
			3.28	3.074

Entropy, H, is defined by:

$$H \triangleq \sum_i p(i) \log_2 \frac{1}{p(i)}$$

Average word length is defined by:

$$\bar{n} \triangleq \sum_i p(i) \cdot \omega(i)$$

Coding Efficiency, η, is defined by:

$$\eta \triangleq \frac{H}{\bar{n}} = \frac{3.074}{3.28} = 93.7\%$$

Figure 8. A Huffman Instantaneously Uniquely Decipherable (IUD) Code for the Statistics Assumed.

length, thus increasing the true information rate. It has been shown that the average weighted wordlength, $\bar{n}$, of a Huffman code is within one bit per word of the maximum possible information rate, H, the entropy for the statistics of a given set of events. This is shown by the expression:

$$H < \bar{n} < H + 1$$

As the family of events gets larger, the average word length increases and the Huffman code becomes more efficient. For example, if we define new events as pairs of the events of Figure 7, the set of 100 new events $p(2,2) = .04, \ldots, p(S,S) = .0004$ will determine a more efficient Huffman code optimal for these new events.

The choice of an IUD code makes the words unambiguous. This provides some tolerance for loss of signal due to fading or noise because the decoder will resynchronize. A disadvantage is that the "noiseless" codes which both systems use can allow small errors to perpetuate in either system until the end of a frame. In this paper, this is deemed acceptable since high resolution has already been sacrificed for a television type of picture, and each frame will be transmitted without prejudice from a previous frame.

To investigate further the expected values of the probabilities in this thesis is unnecessary since (1) the reprogramming of the coding is simple and well known and (2) the statistical structure of different classes of target pictures varies widely. As will be seen later, the reprogramming of the Huffman code involves only a replacement of

the Read-Only-Memory matrix. There is one in the transmitter and one in the receiver. Indeed, it may prove desirable to keep different ROM's on hand for different classes of pictures. No other hardware changes are needed.

3. Common Functions

It was decided to use a slow and a fast oscillator common to both the transmitter and the receiver. This can be done without prejudice to the demonstration. It will be shown that the fast oscillator (400 kHz) can be free running in both the transmitter and the receiver and that the similar functions are carried out at various separate times. The slow oscillator (4800 Hz) can be free running in the transmitter. The receiver slow oscillator must be coordinated with the received signal. If the received signal were taken off the air, the synchronization could be provided from the demodulator by sampling zero-crossings. These samples could be used to control the slow oscillator in the receiver. No other information is carried by the slow oscillator, so for this thesis the transmitter oscillator is shared with the receiver.

Common power supplies were also used at considerable cost saving for this prototype.

B. TRANSMITTER DESIGN

1. Functional Outline

The transmitter produces a steady output pulse stream at 2400 baud. Due to the bandwith limitation, the output approahces a summation of (sin x)/x functions spaced

orthogonally at intervals of multiples of 4.6.67 μsec. In order to provide this uninterrupted stream of pulses, all internal processing of the next coded signal is completed at high speed before the transmission of the current coded signal has been completed. The transmitter functions which accomplish this are set out in Figure 9. The letter in parentheses tells if the function in that block is controlled by the slow 4800 Hz oscillator (S) or the fast 400 kHz oscillator (F) or takes place instantaneously (I).

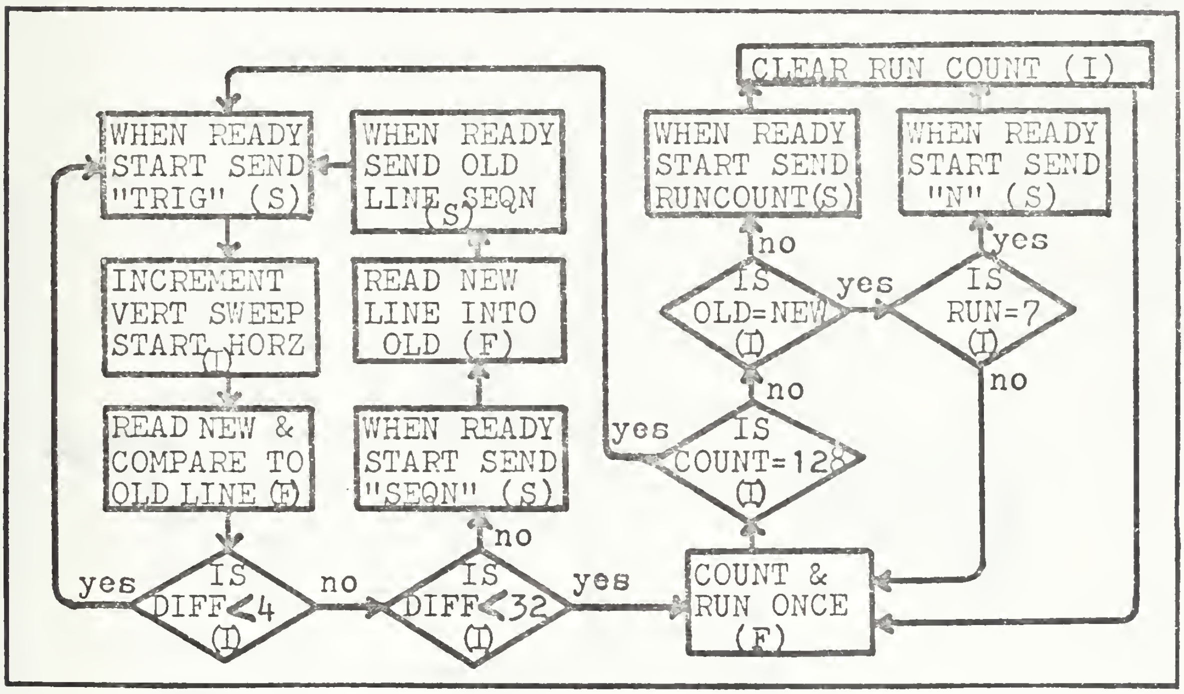


Figure 9. Transmitter Functional Outline.

2. Camera Control

A closed circuit television camera was purchased. A Camera Control circuit board (marked CC) provides a substitute set of triggered asynchronous sweep circuits. This board also converts the analog video output to digital form. There was sufficient room on this circuit board to include both the fast and slow oscillators.

The sweep circuits for horizontal and vertical are the same. They consist of 64 bit binary counters. The output of each flip-flop is connected to a ladder resistor network. This provides a staircase output as the counter counts as seen in Figure 10.

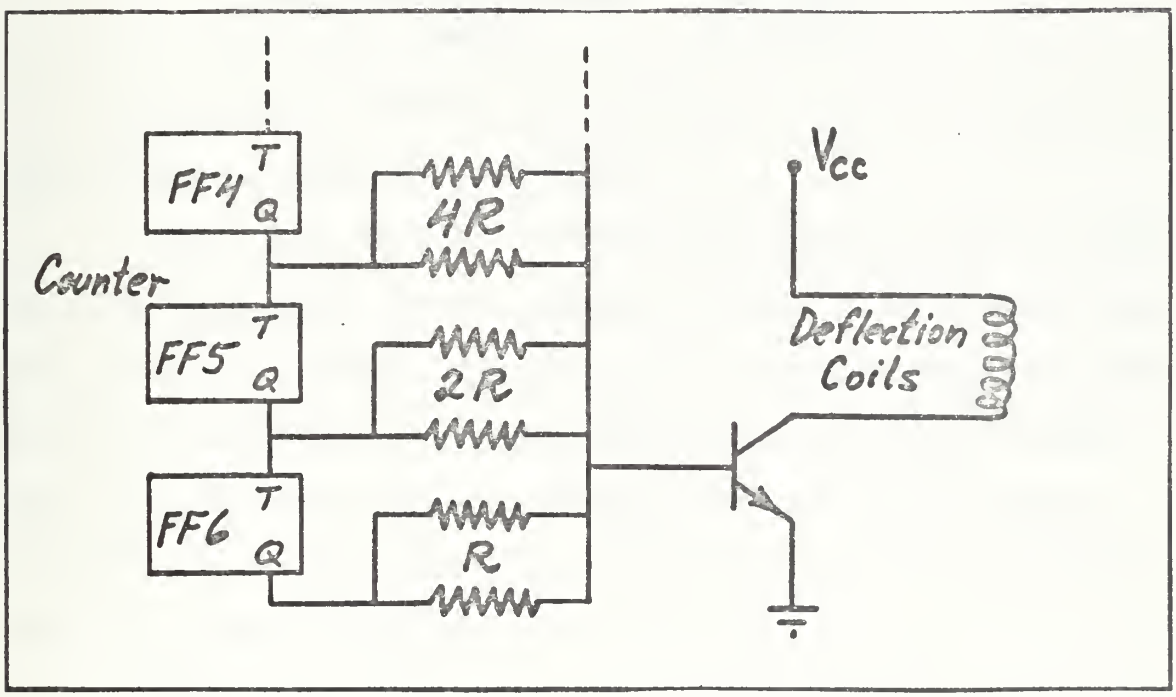


Figure 10. Sweep Circuit Concept

The analog video from the camera passes through an RC approximation to a differentiator. This "sloppy differentiator" enhances the edges and takes advantage of the brain's reconstruction process reported by Koffka [6]. As he explained from the Gestalt-Theorie, this reconstruction is what enables humans to "see" objects in cartoons or sketches even though the cartoons don't fill in the spaces. We recognize political figures by a simple line profile since the eye-brain combination concentrates its attention on edges and fills in the voids with what it expects to find there. The "sloppy differentiator" consists of a resistor capacitor circuit with a step response of the form:

$$v(t) = \frac{V}{2}\left(1 + e^{-kt}\right) \cdot 1(t)$$

All edges with a vertical component are enhanced. Horizontal edges remain, however, unaffected.

The video is then converted to digital form. A common form of A/D converter compares a ramp or staircase function with the analog input with one voltage comparator. That technique employs substantial timing circuitry and is not the most efficient way to quantize the video in 4 levels. Another scheme was devised to accomplish the A/D conversion and it is shown in Figure 11.

This type of converter has three voltage comparators which compare the analog video with DC levels picked off a voltage divider. The 3 thresholds between the 4 voltage levels can be easily adjusted to the levels desired and were set to give a logarithmic response to light intensity.

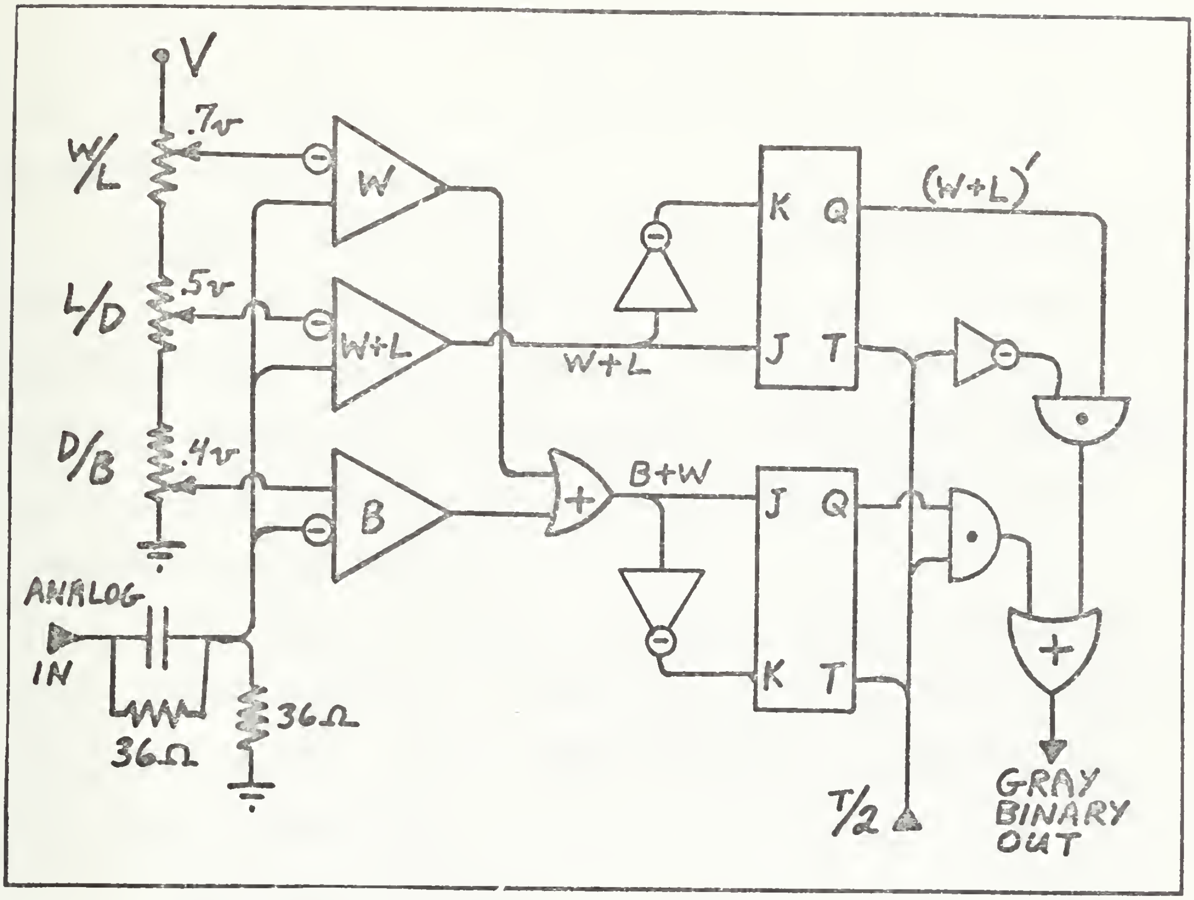


Figure 11. Analog/Digital Conversion Concept.

The distance between the White/Light threshold and the Light/Dark threshold is twice the distance between the Light/Dark and the Dark/Black. The frequency response characteristic of the 3 voltage comparators can be much less than if a ramp/staircase A/D conversion process is used. When the flip-flops are triggered simultaneously, a sample is stored using a Gray code. One bit od data indicates whether or not at the time the sample was taken that the video level was at least above the Light/Dark threshold. The other bit

indicates whether the level was either Black or White, or not. These two bits are in the form that they are stored and carried through the system and consistent with the prediction model in Figure 6.

The clocking oscillators on the Camera Control (CC) board are astable multivibrators. The fast oscillator is inhibited very briefly after the slow oscillator makes a falling transition so that processes elsewhere in the system using both oscillators are allowed proper recovery time between clocking signals.

The logic schematic diagram is shown in Figure 12. The voltage comparators chosen were μA710's which are compatible with TTL. The 15 volt requirement is drawn from the camera power supply.

3. Transmitter Storage

The Transmitter Storage board (marked TS) has the function of storing and comparing a new horizontal line with the old horizontal line. Actually, there are two lines that must be stored because when using a vidicon for image pickup, the new line must be read into storage at fairly high constant speed. This is because the image response is an integrating function of the light energy accumulated since the last sweep. Also, the camera purchased has video amplifiers that have a low frequency cut-off. The comparison between the old line and the new line is done with the predictive scheme described in Section IV.A.1., Figure 6. In addition, this circuit board performs a tally function during the line

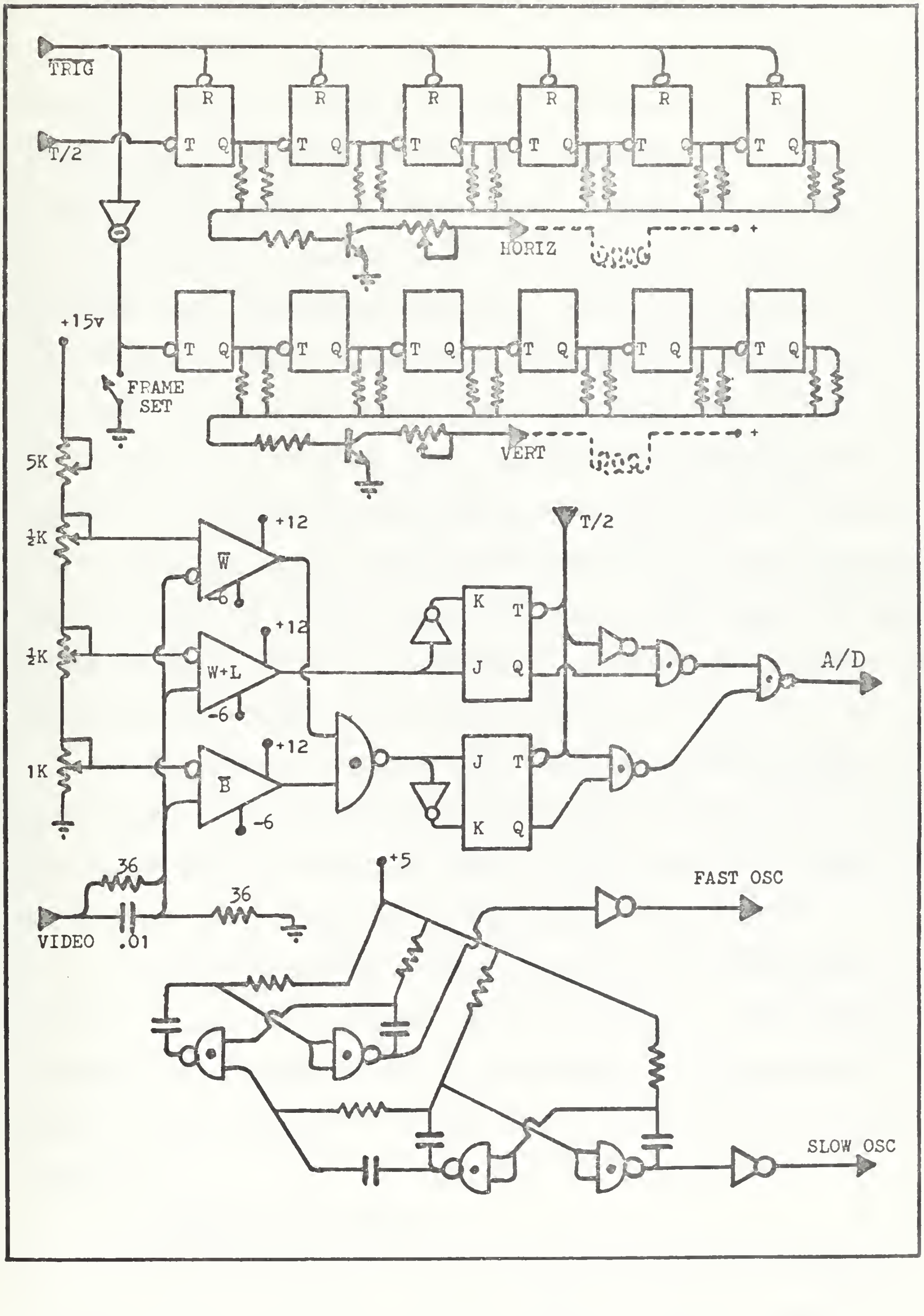


Figure 12. Camera Control Logic Schematic (CC).

comparison to determine what mode of transmission will be used for the new line. The process of reading the line into storage from the camera and making a tally of errors in the prediction is all done during the transmission of the coded signal "TRIG", thus the transmitter is ready to continue.

The line storage is done on two Large Scale Integrated circuit chips designated TMS 3112. Each contain six serial 32-bit static shift registers. Only four are connected in series to provide 128 bits of storage. The other 64 bits of storage are not used. The TMS 3112 only requires one clock. It operates at TTL levels and since it is a static shift register it can store indefinitely at a fixed position with the next bit immediately available. The upper frequency limit of this device for a square wave clock is 830 kHz. The cost of this storage is about 5¢ per bit.

In order to operate the prediction scheme chosen, 4 more bits of storage are required. Since there is no access to the first 3 bits nor the next to last bit on the TMS 3112, these bits had to also be stored on TTL flip-flops.

The Transmitter Storage board also incorporates a 128 bit counter as a memory address register. The system requires this information to keep track of the operating point in the stored line. The logic schematic is shown in Figure 13.

4. <u>Transmitter Coding</u>

The Transmitter Coding board (marked TC) encodes the run length code and the mode control signals "TRIG" and

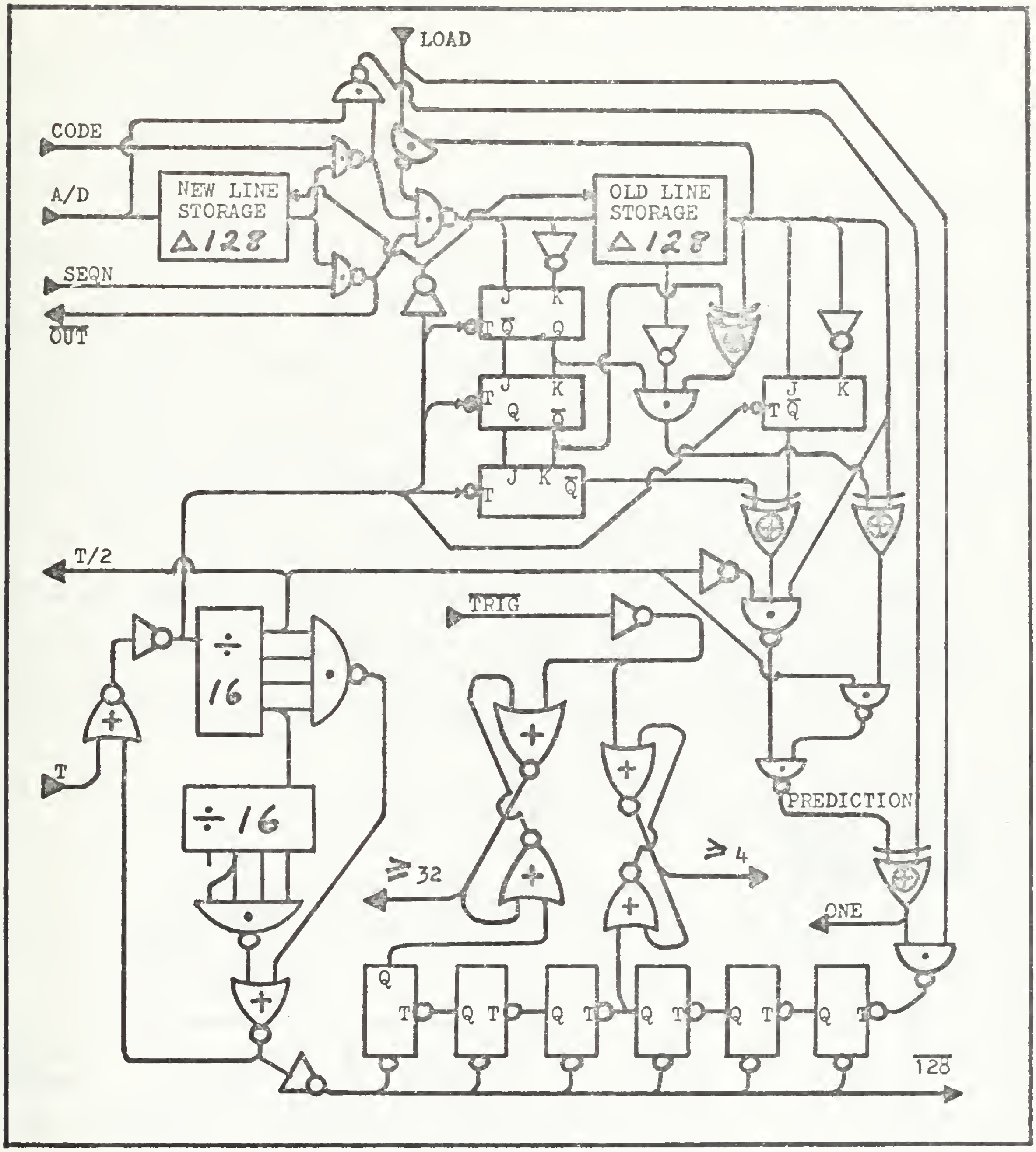


Figure 13. Transmitter Storage Logic Schematic.

"SEQN". During the Sequential Mode of operation, the board is not functional. This board can be considered in four sections: a Bit Counter, a Word Length Counter, a Coder Shift Register and the Coding Matrix.

The Bit Counter counts the bits used in run length coding so that when a prediction needs correction it can be encoded by commanding the appropriate line.

The Coding Matrix generates code words of differing length. As the matrix encodes the characters of the new code word, it also establishes the number of pulses required to read out the variable length code word. The Word Length Counter then provides that number of pulses to the Counter then provides that number of pulses to the Coder Shift Register. See Figure 14. The Word Length Counter operates by counting up to a binary 1,1,1. When the count is 1,1,1, all triggers are inhibited. (Note that $\overline{Q},\overline{Q},\overline{Q}$ is 0,0,0 and the triggers operate on a negative-going input.)

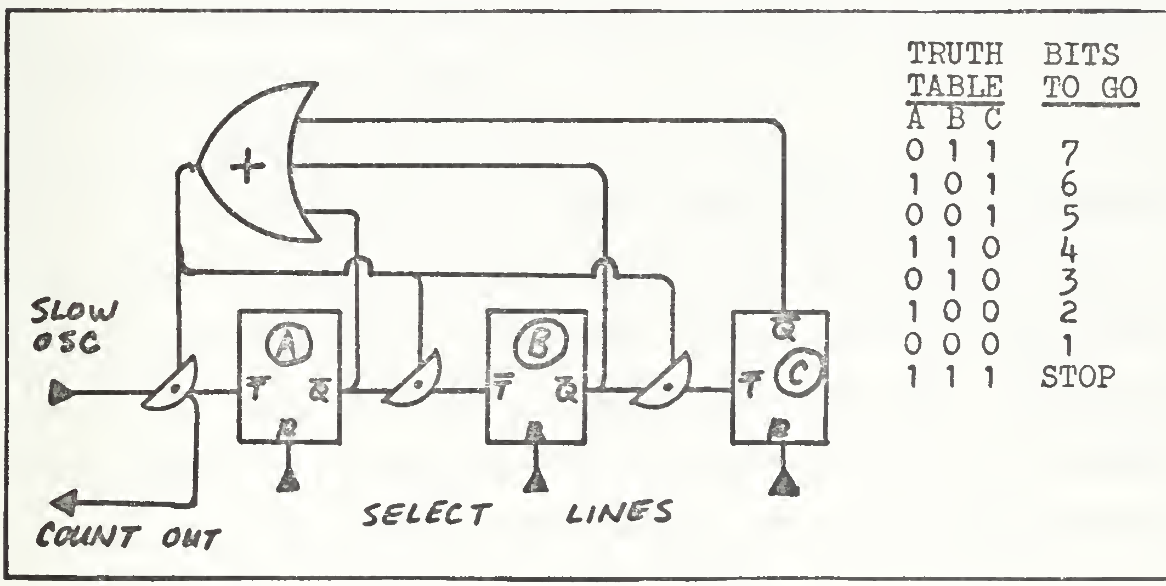


Figure 14. Word Length Counter Concept.

When a code word is to be sent, the appropriate predetermined flip-flips are cleared so as to set Q to 0. The counter then counts at the slow oscillator rate until the coded word has been sent, at which time the triggers are again inhibited.

This Coding Matrix is unusual in that it operates at two levels. The Bit Counter side is normally low whereas the Word Length Counter and Coder Shift Register side of the matrix is normally at high level. The matrix was constructed as a diode matrix although the coding could be done on a Read-Only-Memory with substantial space savings.

The Coder Shift Register always reads a 1 into its first stage. Predetermined selection lines are deenergized. This clears the appropriate outputs to 0 to form the code word.

Figure 15 shows the logic schematic diagram for the Transmitter Coding board.

5. Transmitter Control

The Transmitter Control board (XC) has the function of overall program coordination of the transmitter. The heart of the board is the Moder Orderer network that determines the mode of transmission for the new line. Figure 16 shows how the signals from the tally section of the Transmitter Storage board and the signal "GO" from the Transmitter Coding board determine the mode order.

Each of the three possible orders then sets a latch that starts aprocess that sets a second latch that completes the control of that mode. The latches are all reset before

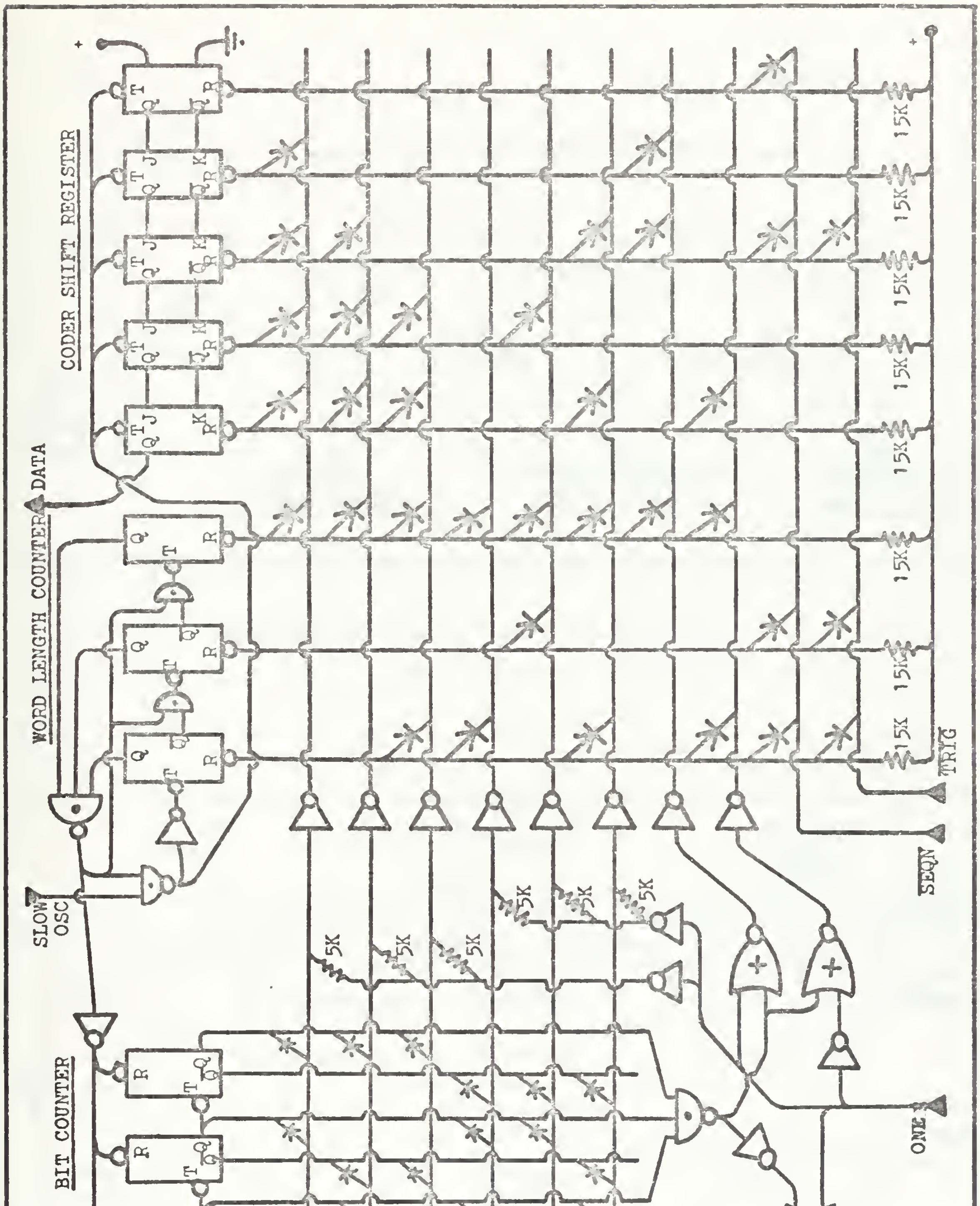


Figure 15. Transmitter Coder Logic Schematic (TC).

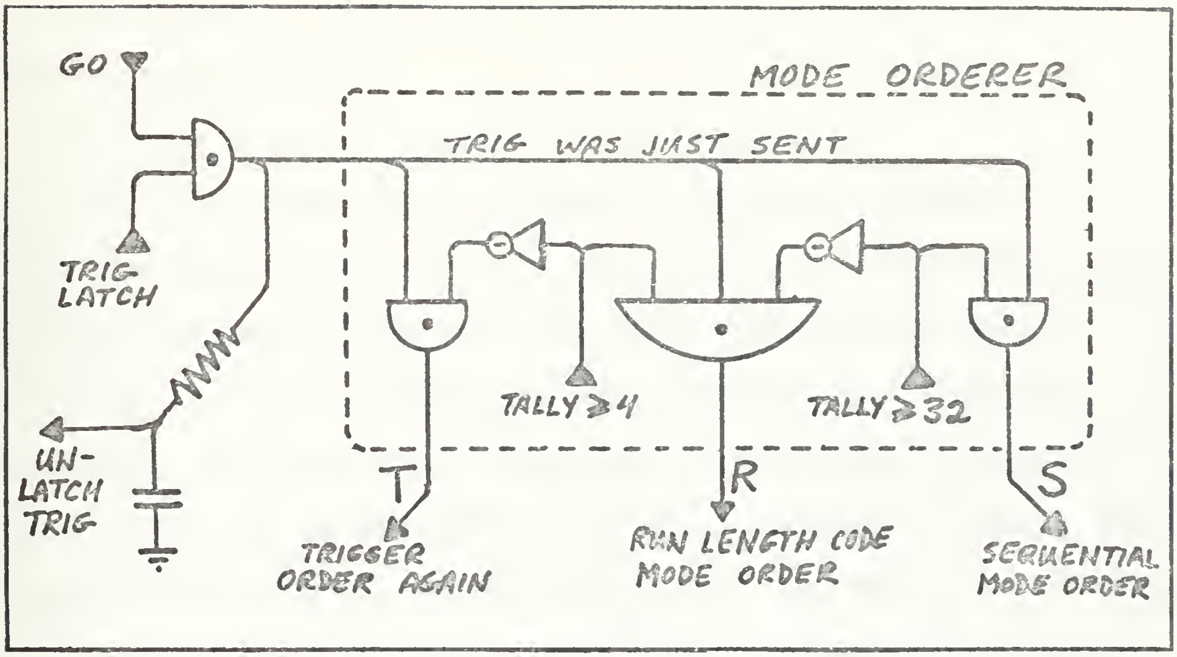


Figure 16. Mode Orderer Concept.

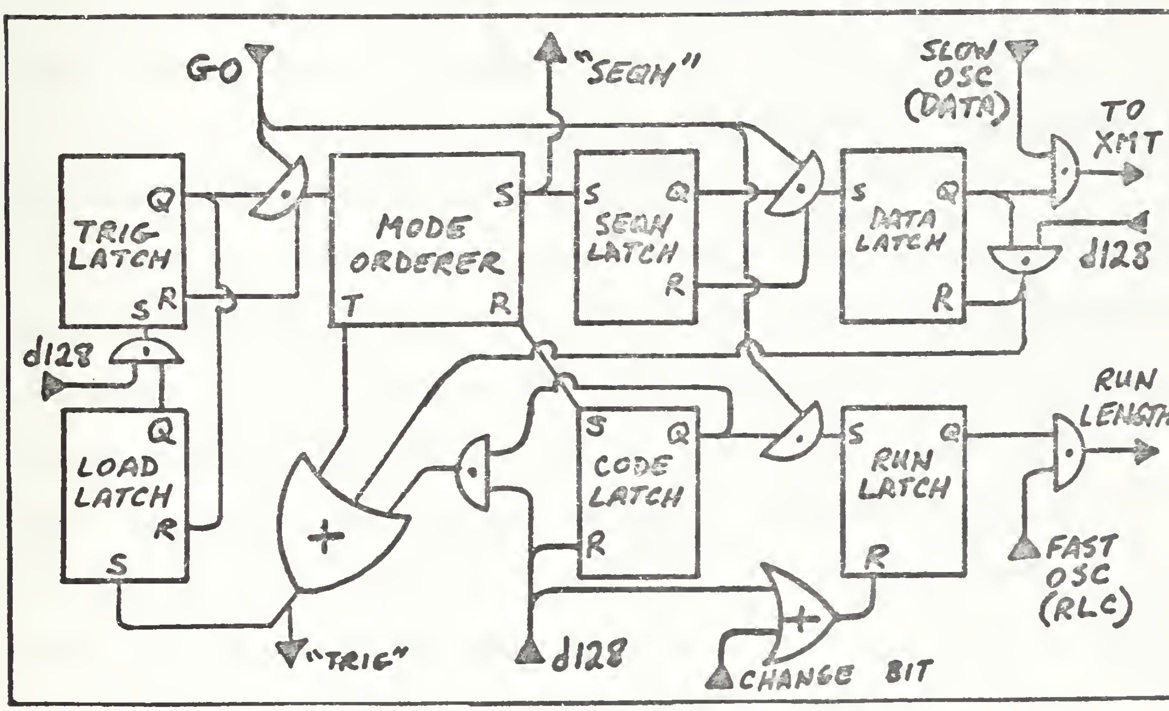


Figure 17. Control Logic Concept.

the next order is ussued. Figure 17 is a logic diagram of this control system.

The process operates as follows:

a. From time to time a trigger is ordered on T from the Mode Orderer. This sets the Load Latch and also resets the Tally Counter. The Load Latch orders that a horizontal line be read from the camera into transmitter storage. While this is being done, a comparison with the predicted line is made which yields a new tally count. As soon as 128 bits of the new line have been read into storage, the Trigger Latch is set. This halts the high speed input into storage and holds the new tally count. In the meantime, the Transmitter Coder has been transmitting the code word "TRIG". When the word has been sent, the Trigger Latch is cleared and the new tally count is read by the Mode Orderer. This results in a new order.

b. When the tally is less than 4, a new trigger is ordered. This begins the process described in 5.a.

c. When the tally is from 4 through 31, the Code Latch and the Run Latch are both set. The Run Latch allows the fast oscillator to count bit by bit from left to right across the new line to the first bit which must be changed. This count, however, never exceeds 7 even if no change is indicated. The reason for stopping at 7 bits regardless of the correctness of the predictor is simply a hardware limit to prevent too large a number of code words and to keep the

length of the code words within a manageable limit. When this short count is completed, the Run Latch is reset and the appropriate code word is set by the Transmitter Coder. This code work is transmitted at 2400 baud. When the word transmission is complete, the Run Latch is set again. This process of rapid short count followed by sending the code word and then repeating is done until all 128 bits of the line have been addressed. At that time, the Code Latch is reset and a new trigger ordered. Then the process described in 5.a. is repeated.

d. When the tally is greater than 31, the Mode Orderer orders "SEQN" and sets the Sequential Latch. After the code word "SEQN" has been transmitted, the Data Latch is set and the Sequential Latch is reset. The Data Latch then transmits the new line sequentially to the receiver at the 2400 baud rate. As soon as 128 bits have been transmitted, the Data Latch is reset and a new trigger ordered. Then the process described in 5.a. is repeated.

The function of the Data Latch is to either connect the sequential data to be transmitted or the code words from the Transmitter Coder to be transmitted, when set or reset respectively. Before this assembled bit stream can be transmitted, however, another process is required to limit the output bandwidth. An approximate (sin x)/x function forming network was designed which sums the successive signal bits into a band-limited signal of the form:

$$s(t) \approx \frac{1}{2} + \sum_{n=1 \to \text{LARGE}} a_n \cdot \frac{\sin(t+n\Delta)}{t+n\Delta}$$

Where a_n is either +1/2 or -1/2, n is whole, and Δ = 416.67 μsec.

The objective of this design was to provide a long serial-in-parallel-out shift register with both high and low output points. The output bus has a load which acts as an energy sink. A plot of the (sin x)/x function was divided at equal intervals. The output of each shift register stage then supplies energy to the bus through a resistor. The resistor is chosen to provide energy in proportion to the time integral of (sin x)/x in its appropriate interval. The sign is controlled by taking the "Q" or the "not Q" output. Data to be transmitted is entered into the shift register at intervals of π radians (here 416.67 μsec). Convenient clocking speeds can be 4800 Hz times 2^n, n whole, with the shift register 6 x 2^n stages long. This sums 3 positive excursions and 2 negative excursions of the (sin x)/x function. Figure 18 shows the simplest form of this signal forming network with n = 0.

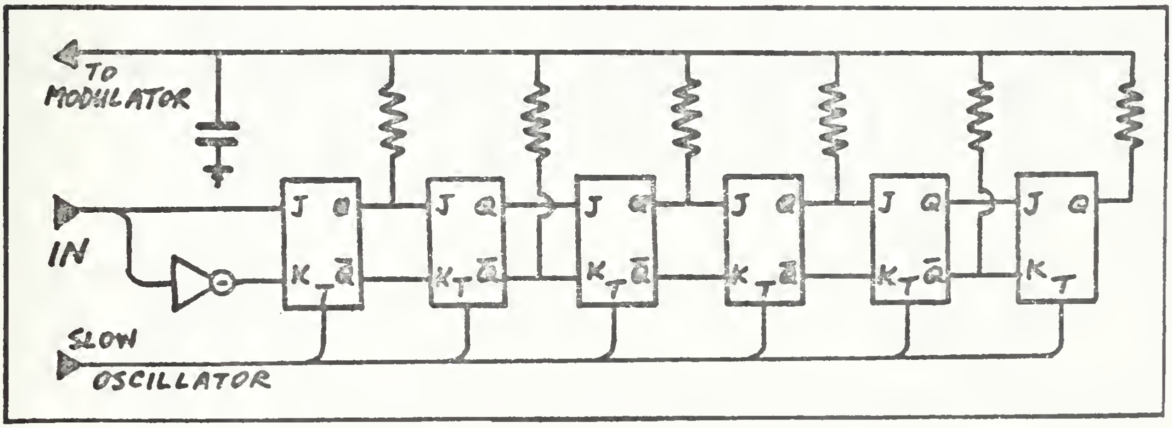


Figure 18. (Sin x)/x Synthesizer.

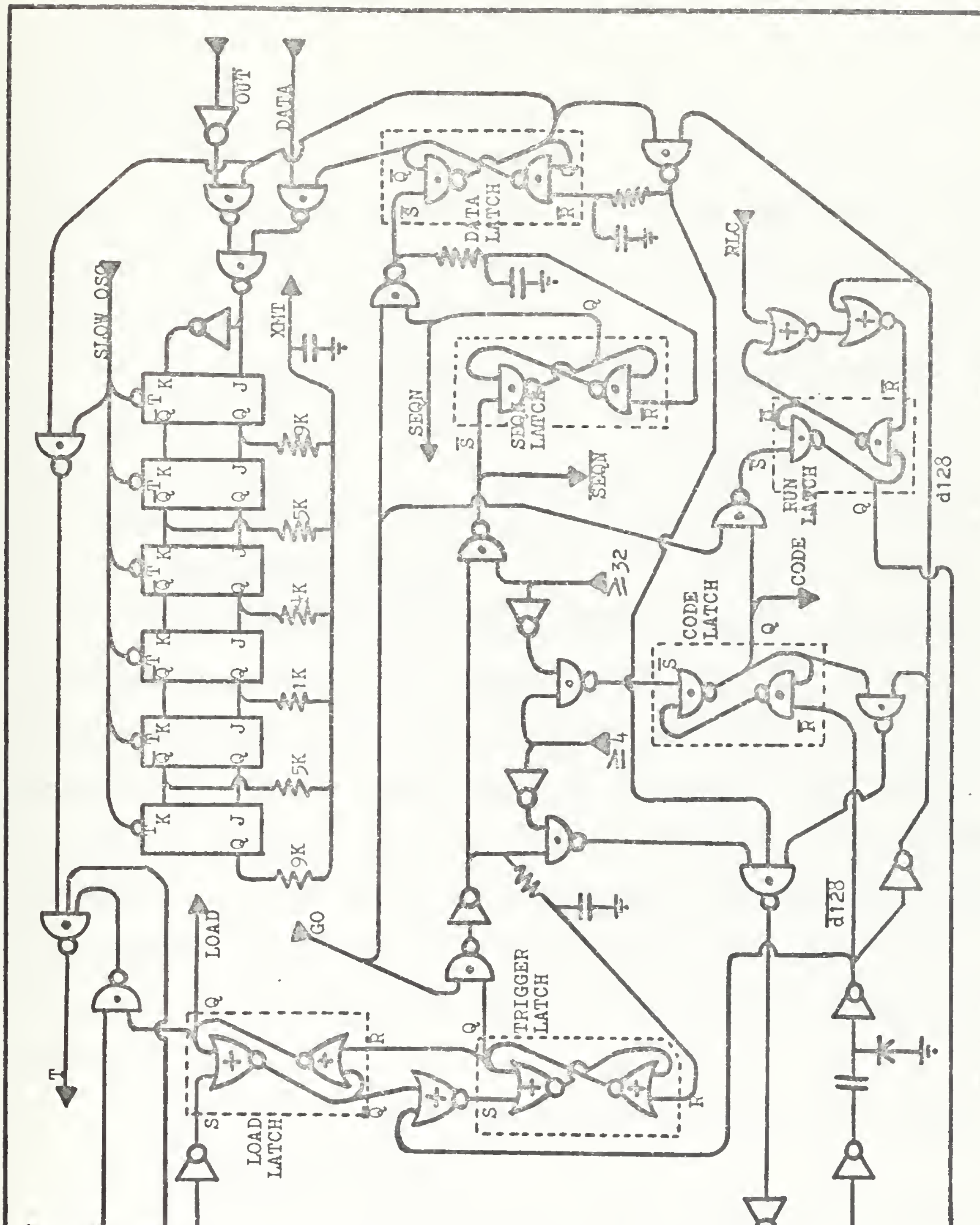


Figure 19. Transmitter Control Logic Schematic (XC).

A six stage shift register was chosen because it does not require a different oscillator frequency. A much better signal can be generated with a 9600 Hz clock and a 12 bit shift register. The load resistance and the capacitor smooth the clocking transitions. The C is chosen for an RC constant of half the clock interval. From XMT the signal goes to a distant receiver.

Figure 19 shows the logic schematic diagram for the Transmitter Control Board.

C. RECEIVER DESIGN

1. Functional Outline

The receiver must determine the proper operating mode and then decode the signal, update the line it has stored and read it out onto a cathode ray tube. Since the Repeat Mode and the Jump Mode both are controlled by code words, the receiver normally will be decoding. The exception to this is for the 128 bits immediately following the word for "SEQN". After the 128 bits, the receiver reverts to decode. If more "SEQN" is needed, the transmitter will send the order again.

The receiver functional program is shown in Figure 20.

2. Control & Storage

The receiver Control & Storage (CS) board controls all of the functions of the receiver. In the control section, there are 3 latches. The Code Latch, when set, loads the next 128 bits directly into the line storage and then the

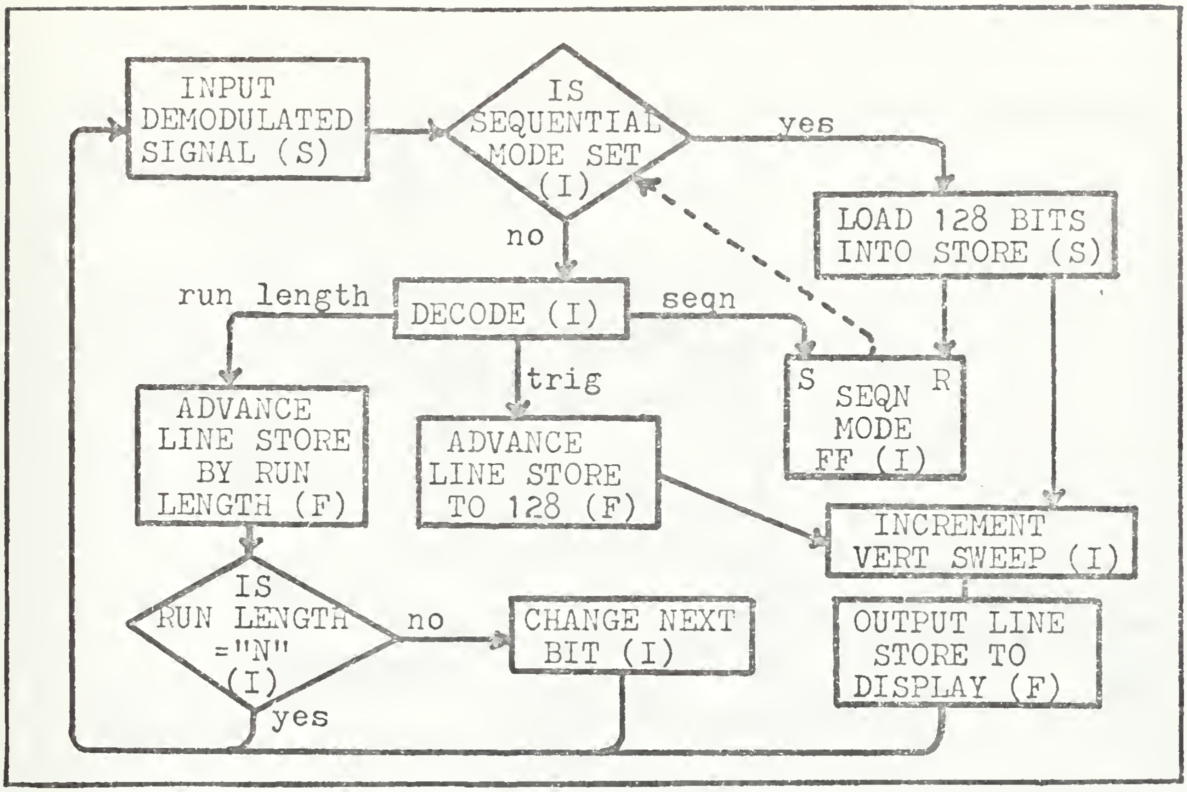


Figure 20. Receiver Functional Program.

latch is reset. When the latch is reset, it switches the bit stream to the decode matrix. When a "TRIG" signal has been received by the decode matrix, then the Trigger Latch is set. Figure 21 shows that if the line is not yet completed (i.e. 128 is not true) then a "circulate" signal is generated. This allows the line to be clocked around to the 128 position (this will be less than 8 bits).

As soon as the 128 position is reached after the Trigger Latch has been set, the Display Latch is set. This resets the Trigger Latch and also generates a "circulate" signal for 128 bits. This causes the stored line to be read out to the D/A converter for the display oscilloscope. The line is also returned to its former position in storage.

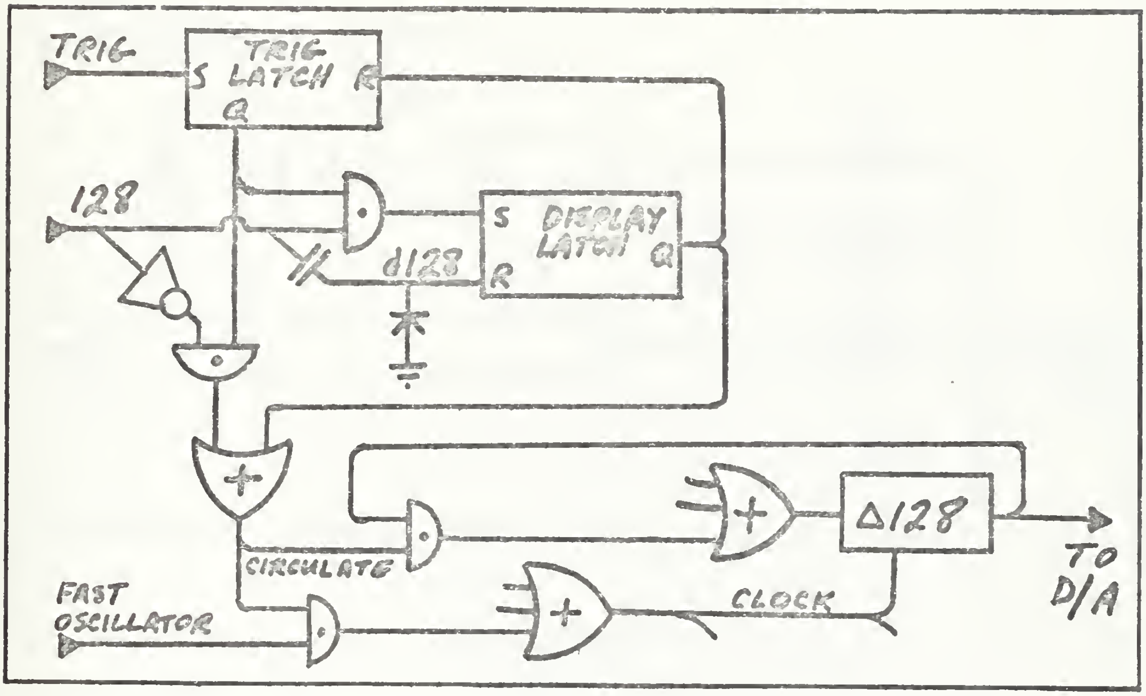


Figure 21. Trigger Control Concept

Further, the signal setting the Display Latch increments the vertical sweep and triggers the horizontal sweep of the display oscilloscope.

The vertical sweep section of the Control & Storage board counts the number of sweep triggers decoded in the same manner as the vertical sweep on the Camera Control board. The vertical sweep section provides a vertical signal to the display oscilloscope.

A D/A converter was designed to restore the processed signal to logarithmic video. Figure 22 shows the converter concept. This scheme has a readout for hald the T/2 clock cycle and the display is kept black during the other half.

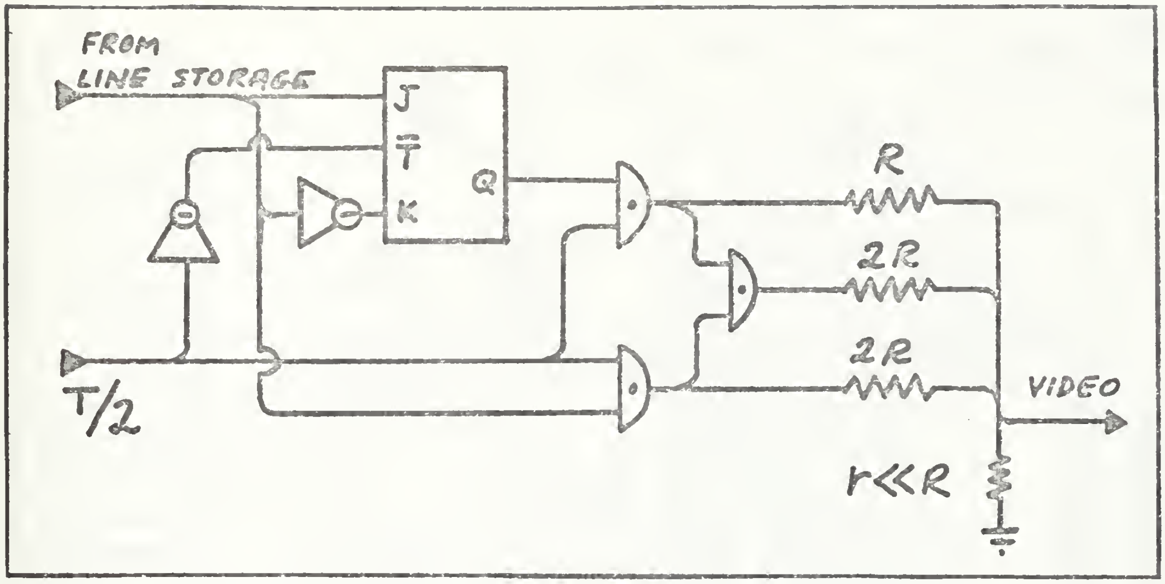


Figure 22. Logarithmic D/A Concept

The logic schematic for the Control & Storage board is shown in Figure 23.

3. Decode Matrix

The Receiver Decoder Board (RB) contains the Decoding Matrix. The logic schematic for the Receiver Board is shown as Figure 24. When a Huffman code word is clocked into the Decode Register, the Decode Matrix intepprets the word and causes two independent actions. First, the length of the current code word is placed in the Word Length Register. This initiates a series of slow clock pulses which clocks the following word in sequence into the Decode Register. Each code word is read from the A position of the Decode Register back its own length so that counting out one decoded word by its own length places the new word in the right-justified position of the Decode Register. The word for SEQN

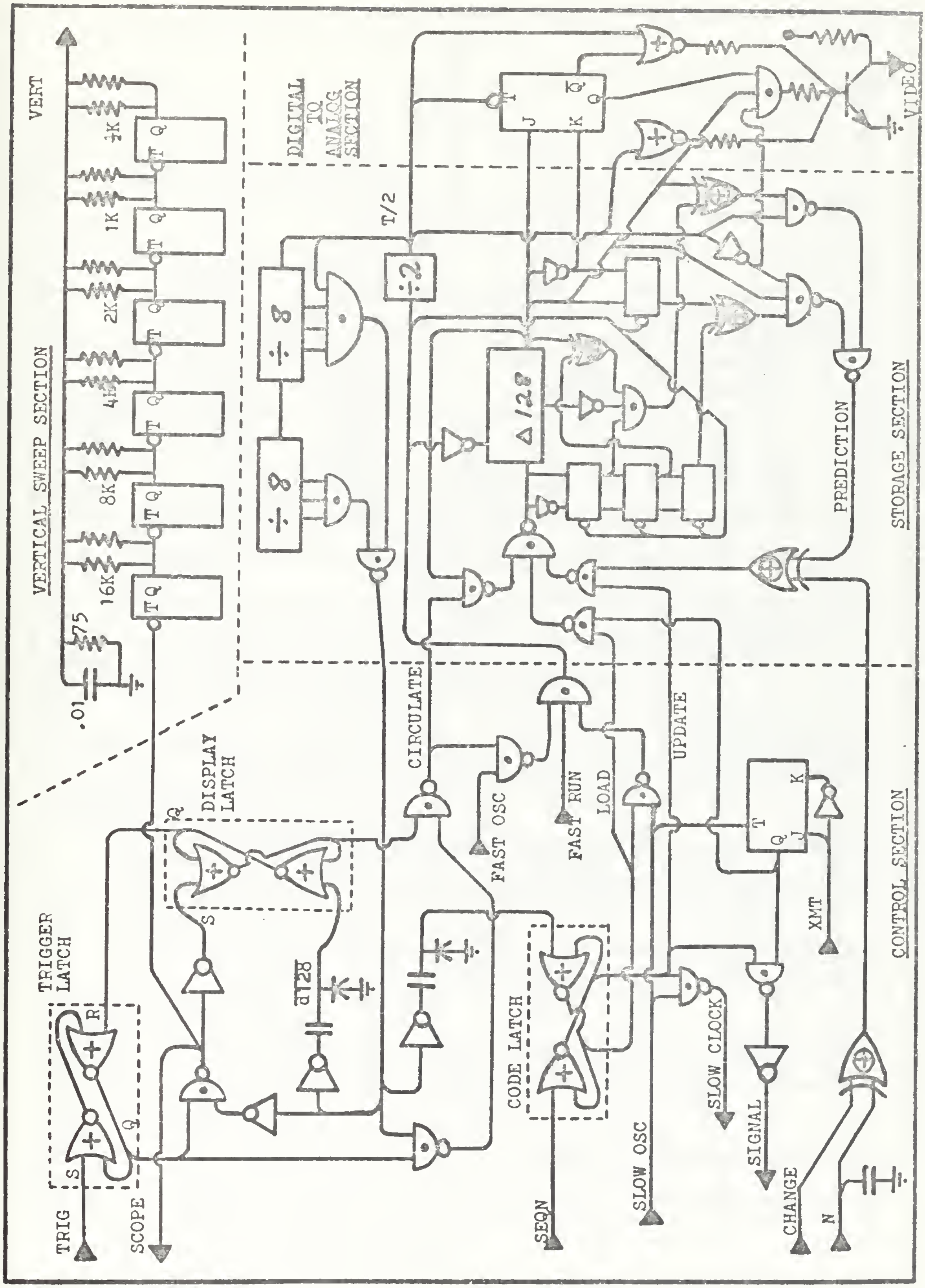


Figure 23. Control & Storage Logic Schematic (CS)

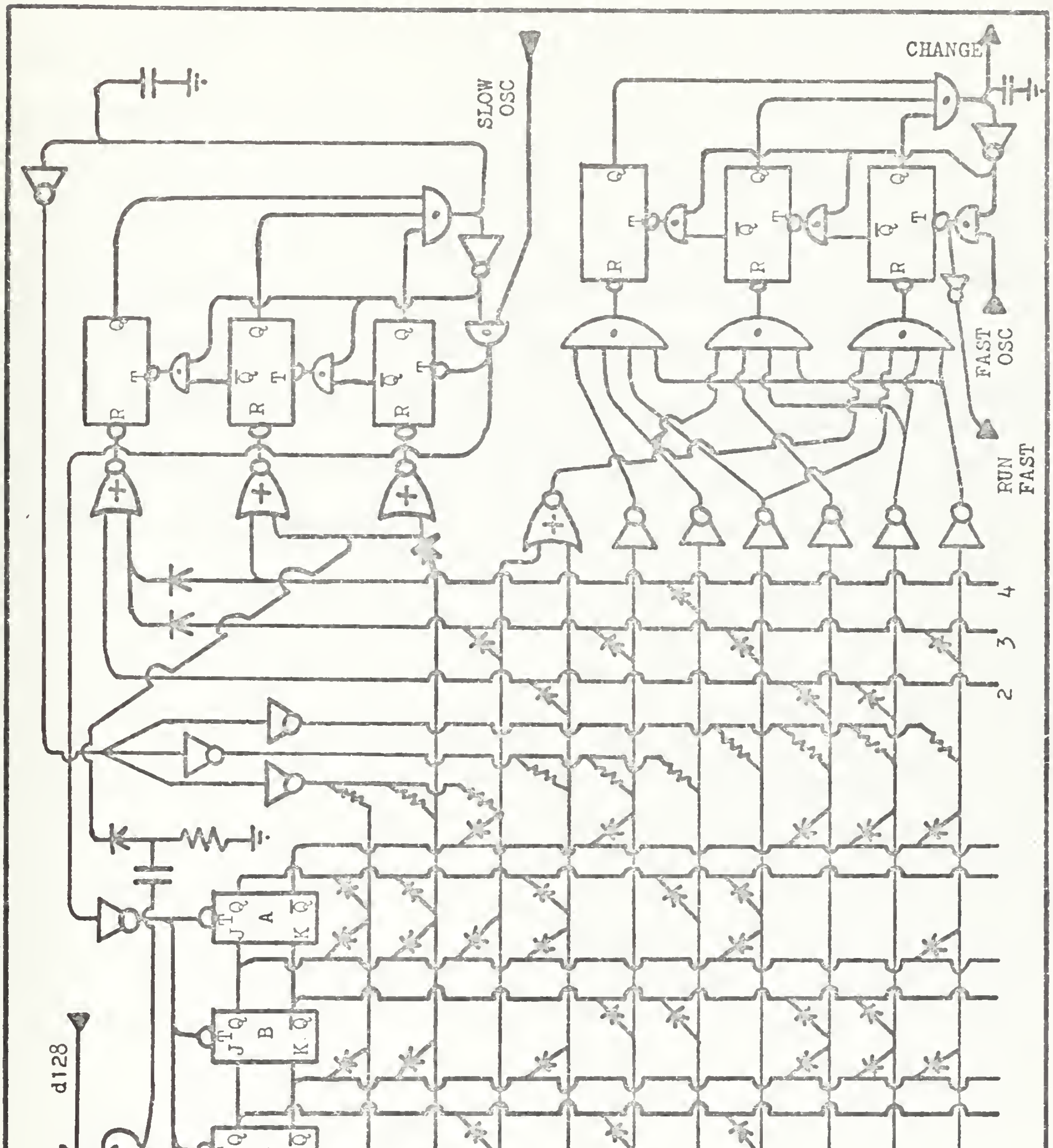


Figure 24. Receiver Decoder Board Logic Schematic (RB)

is a 5 bit word which does not immediately set the Word Length Register. The order to clock 5 bits comes after the 128 Sequential bits have come. The next 5 bits are then clocked into correct decoding position A,B,C,D,E.

The second action is to set the Run Length Counter to the number of bits to the next difference from the prediction. This distance is then clocked into the Line Storage with the Fast Clock. The Fast Clock, at 400 kHz can complete any operation before the slow clock can complete even the shortest incoming word.

V. CONCLUSIONS

This thesis has described a practical design of a digital encoding and decoding processor which reduces the bandwidth required to transmit images. The design employs a hierarchy of transmission modes. This allows the transmitter to scan a video line and then choose the most efficient mode of 3 to send the line. One of these modes uses variable-length optimal coding to improve coding efficiency. An algorithm was described which predicts the value of a picture element from two dimensions, thus reducing the amount of information needed to be sent.

The equipment described was built according to these plans. Parts of the system have been tested and found satisfactory. All the coding/decoding functions and their associated Run Length Counters and Word Length Counters have been tested. The 129 bit line storage system has also passed functional tests. The whole system lacks final check-out due to a continuing shortage of only a few components. The equipment now built can and will serve as a test-bed for parameter investigation. Some of these areas of interest are:

(1) Study the effect of the system when the aspect ratio is changed to 3/2 (picture 96 by 64 elements).

(2) Study changing the tally threshold. (How many bits should be off prediction to determine the Jump Mode, etc?)

(3) Check to see if the best number of quantization levels was chosen. (Seven bits might control 3 picture elements at 5 levels.)

(4) Check phosphors on receiver oscilloscopes to ascertain the best persistance value.

(5) Analyze the statistics of possible target photos and investigate more elaborate prediction matrices.

APPENDIX A. CONSTRUCTION INFORMATION

Transistor-Transistor-Logic (TTL) was chosen for as much of the logic as possible. This was because it is inexpensive, readily available and there is enough logic variety to make implementation easier. Only one 5 volt power supply is required for the TTL. The Dual JK Flip-Flops (7473) have 3 salient characteristics: first, the trigger operates on a high to low transition; second, the reset function occurs when the reset line is low; third, as a counter, the trigger only alternates the output if both J and K inputs are high. These conditions necessitated connecting several extra terminals to the supply source. The RS Flip-Flops, used as simple latches, were made from Quad two-input NOR gates (7402) connected in pairs. Where the RS inputs were inverted, the NAND gates (7400) were used connected in pairs. Although the TMS 3112's did not require two clocks, they did require two power supplies. The μA710 voltage comparators also required a separate power source. Figures 25 through 37 show the detail of the integrated circuit connections. It also shows the circuit card design and their interconnection. Figure 38 shows some of the completed circuit boards. Figure 39 shows the assembled system.

When the design of this voiceband television system was completed, the circuit boards were laid out at double actual size. Opaque tape was then placed on translucent

white drafting paper. Five of the six circuit boards had to be double-sided so eleven layouts were required. The translucent sheets were then backlighted and photographed using a high contrast film. The photographic process used gave a 2:1 reduction onto the negative.

G-10 Epoxyglass circuit boards were then coated with negative photo-resist and prebaked. The negatives were then clamped to the coated circuit boards and contact exposures were made. One exposure was made with sunlight. The other 10 were made with a sunlamp. After the resist was developed to remove the unexposed resist, the boards were postbaked to increase the protection of the remaining unexposed resist from the etchant.

Two kinds of etchant were used. Three boards were etched with ammonium persulphate. No mercuric chloride catalyst was used, even though this is commercial practice, because of its high toxicity. The other three boards were etched with a ferric chloride solution.

Components were then mounted on the boards. Sockets were used for all integrated circuits for ease of handling. Every board had some jumpers since even with double-sided boards, other additional connections were required.

A rack was available with edge connectors which were interconnected according to a cross-connect sheet written for that purpose.

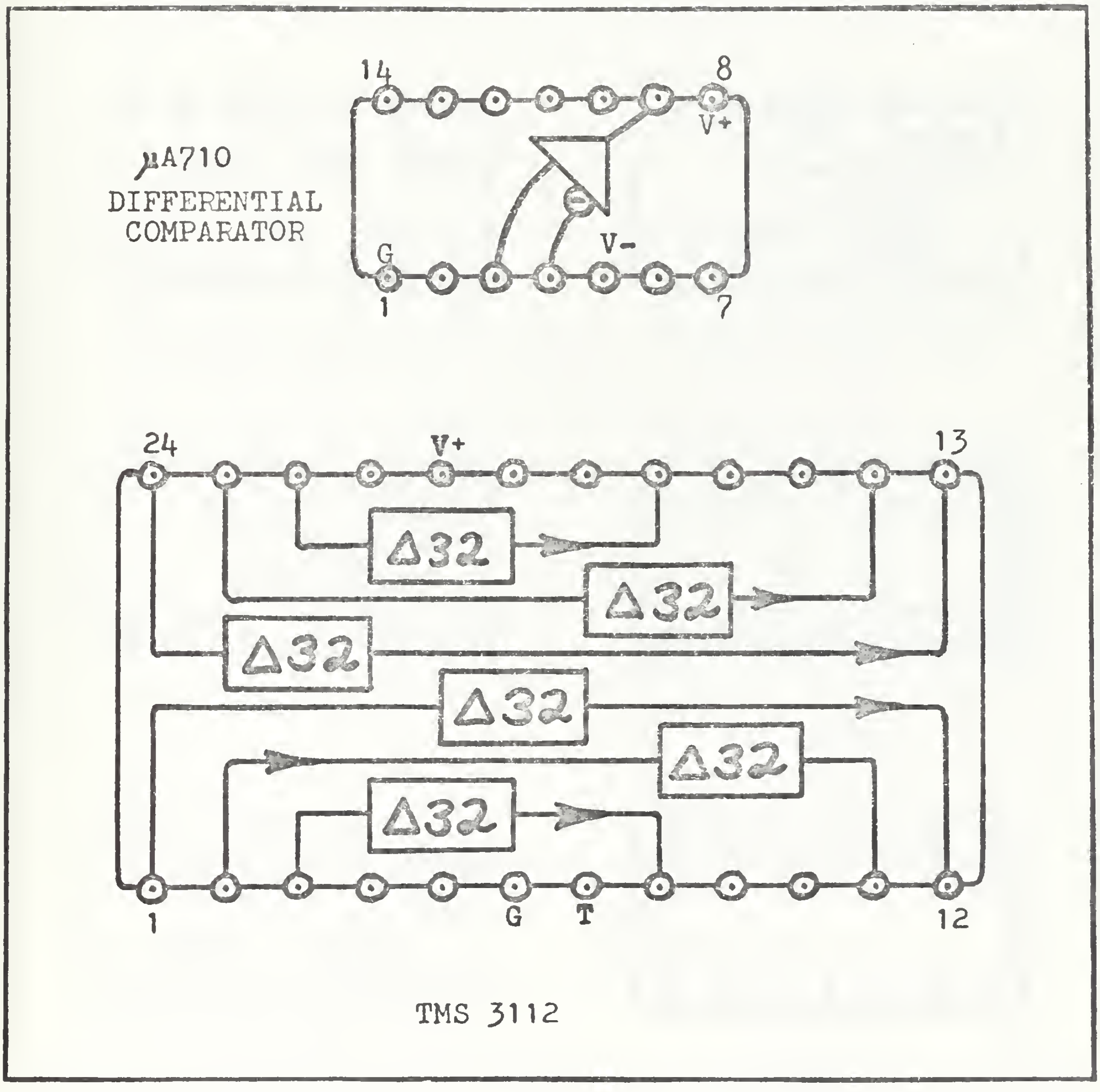


Figure 25. TMS 3112 and µA710 Layouts.

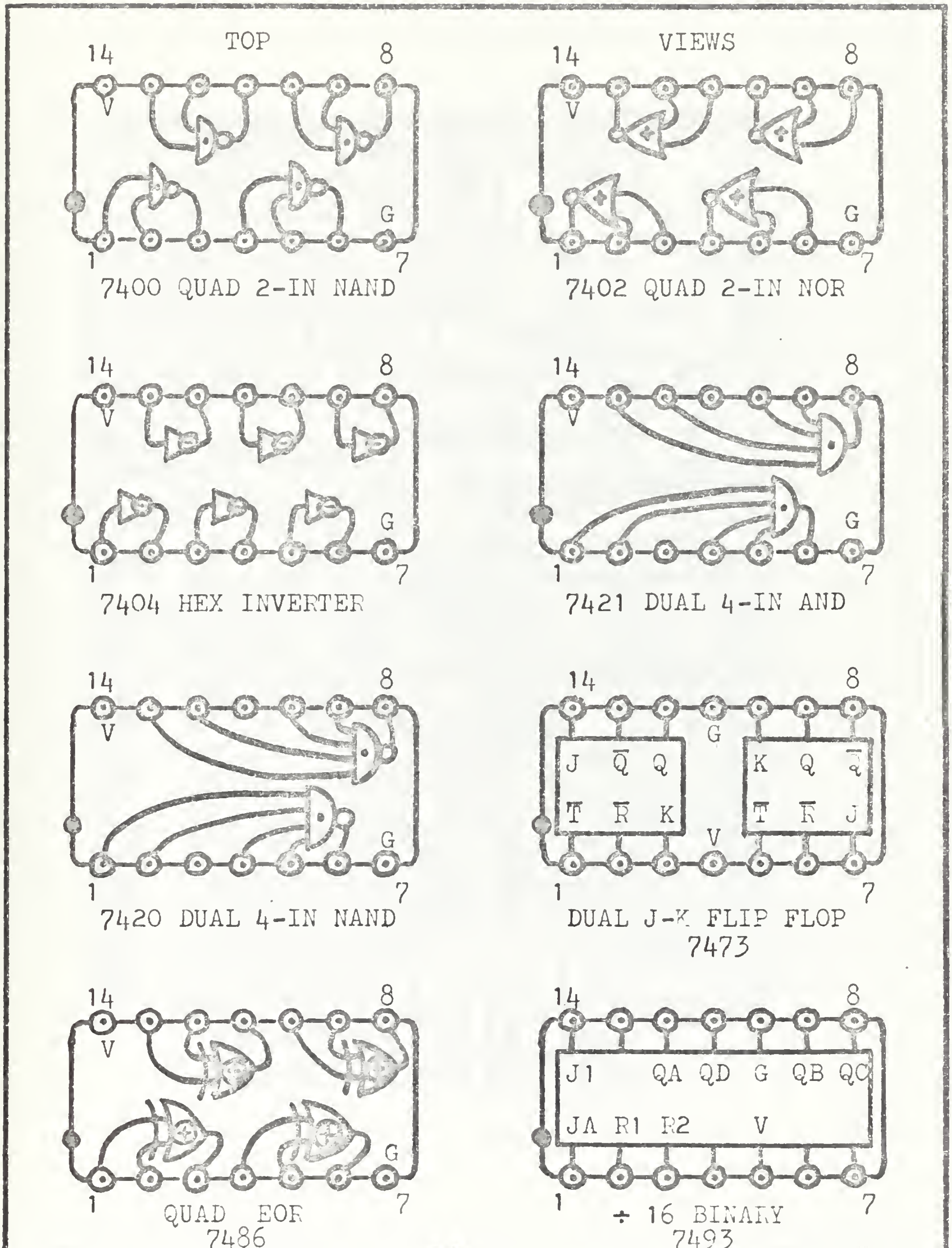


Figure 26. 74XX Series TTL Layouts.

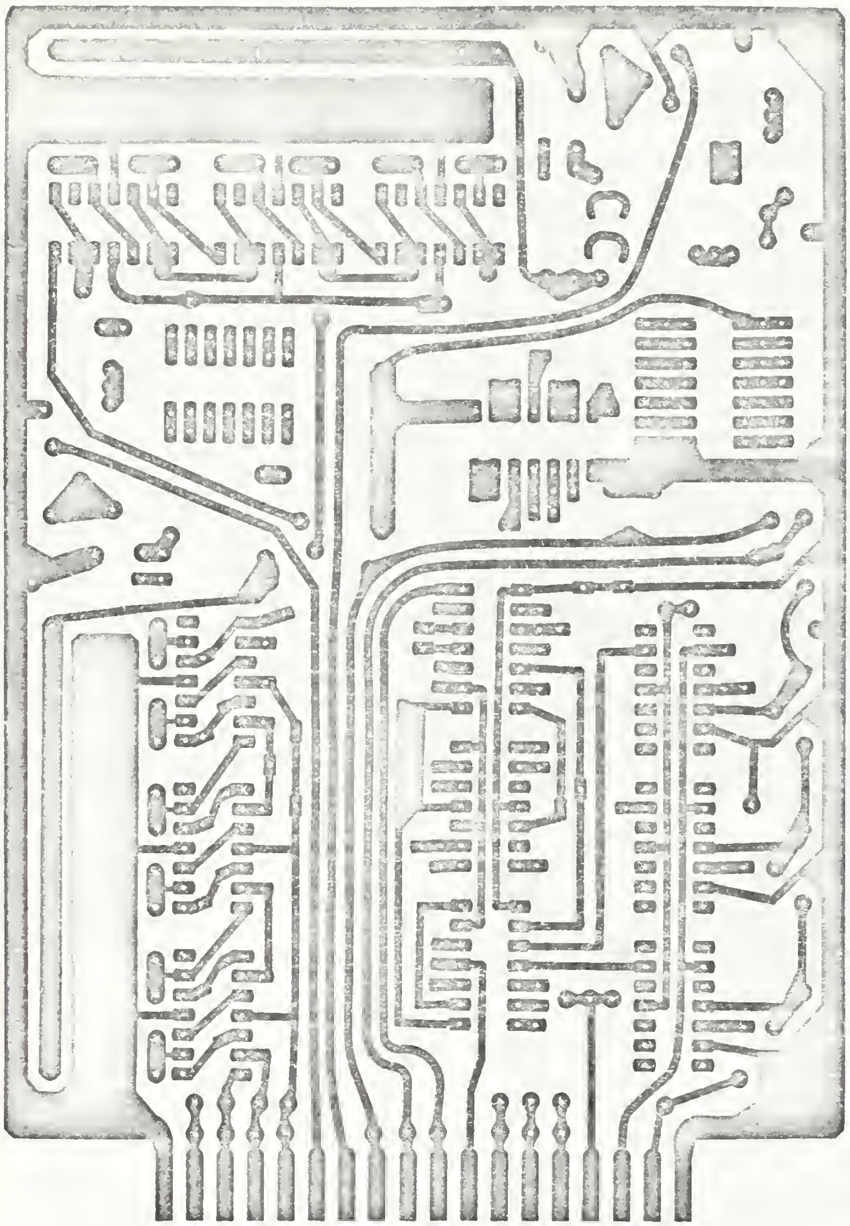


Figure 27. Bottom Foil of Camera Control Board

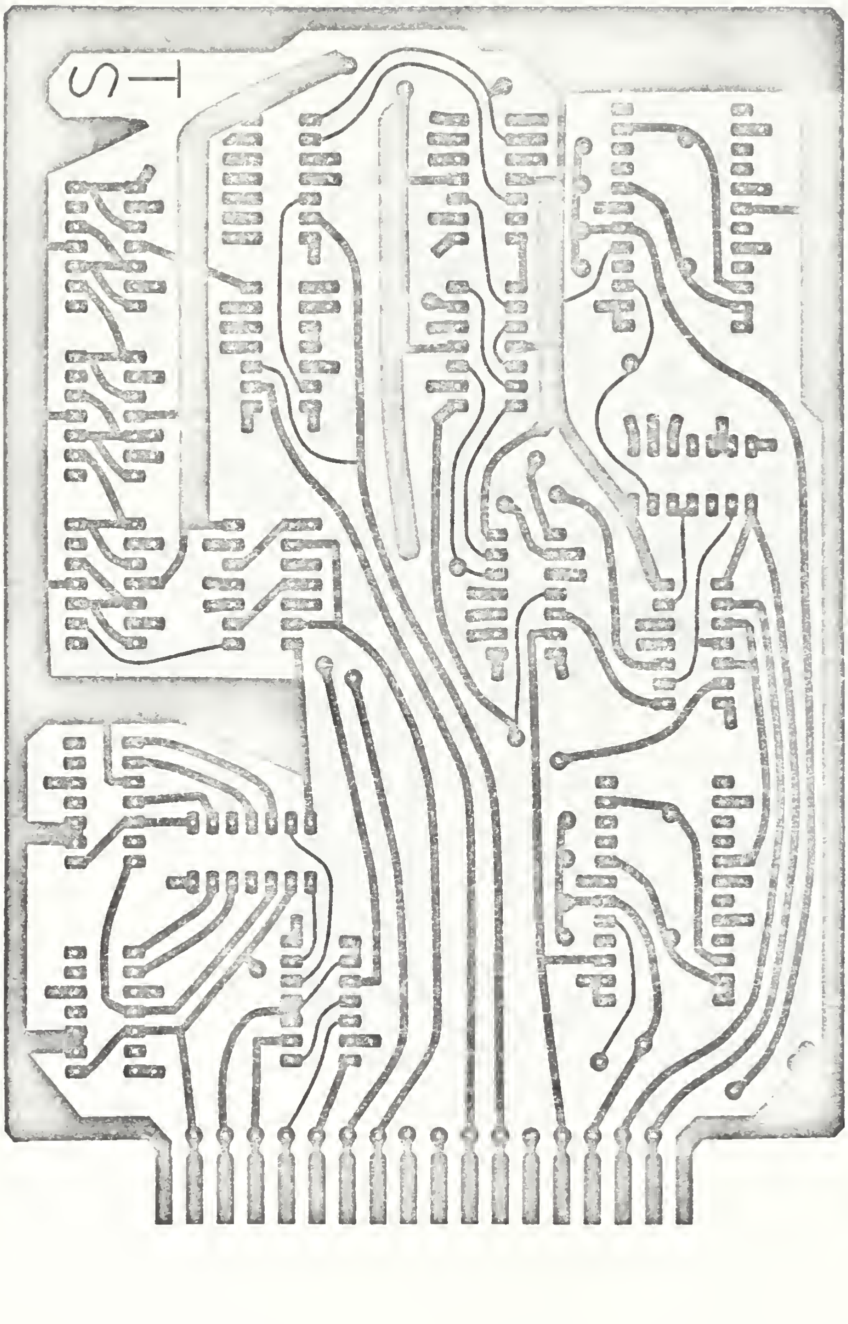


Figure 28. Bottom Foil of Transmitter Storage Board.

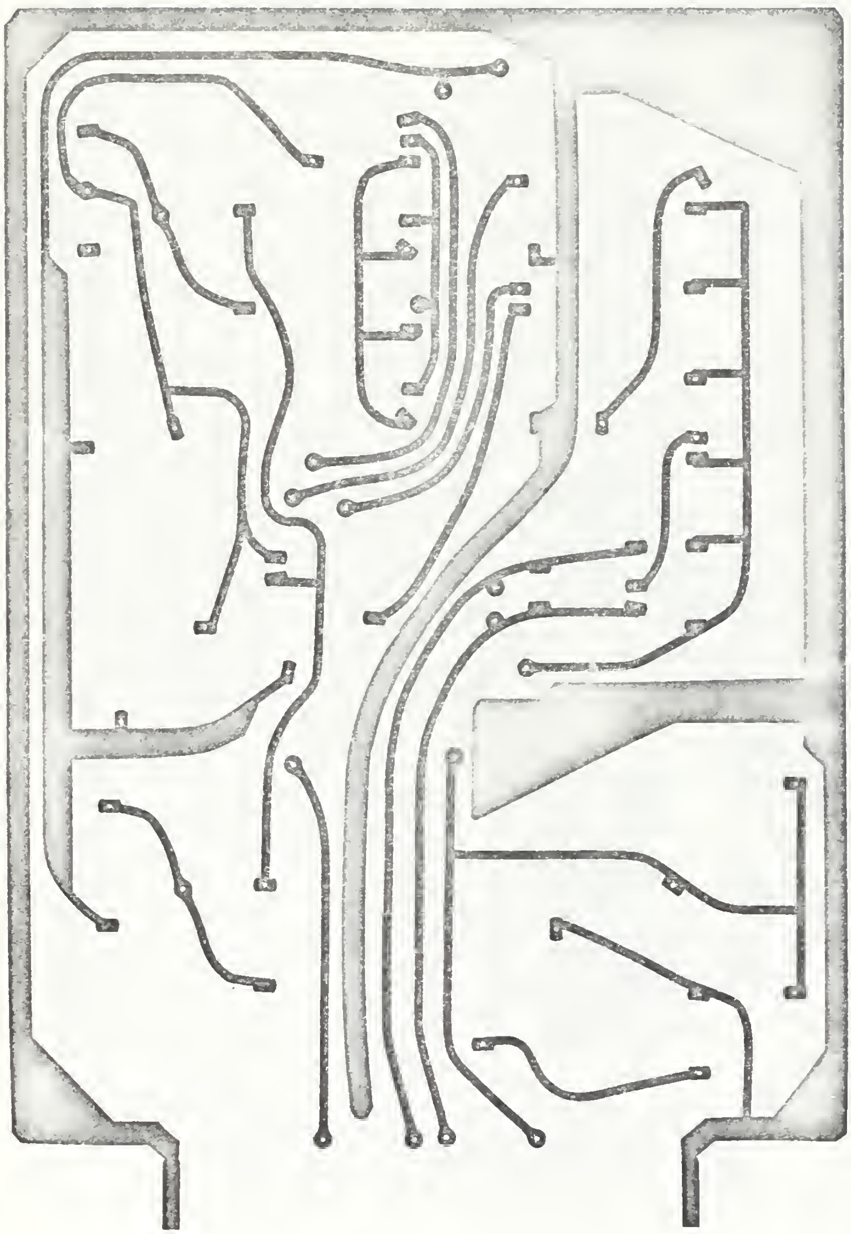


Figure 29. Top Foil of Transmitter Storage Board.

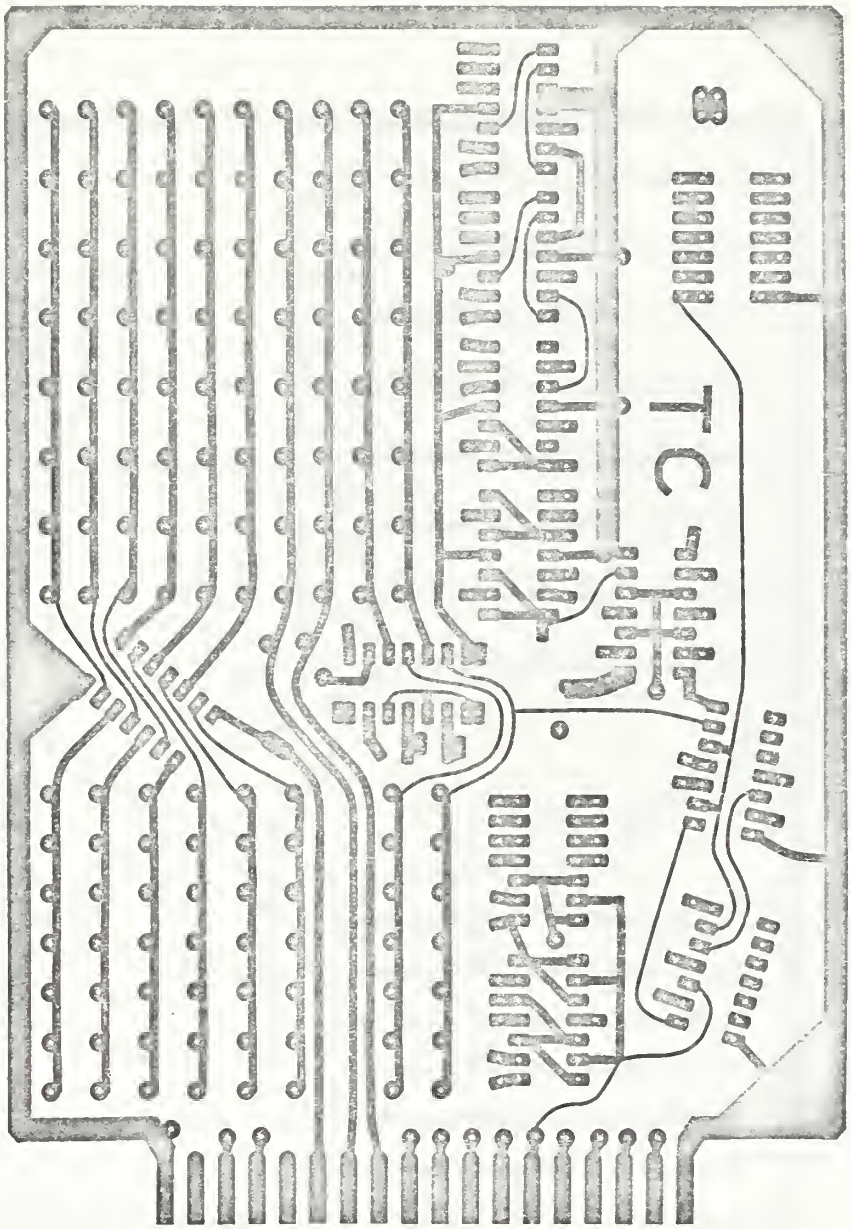


Figure 30. Bottom Foil of Transmitter Coding Board.

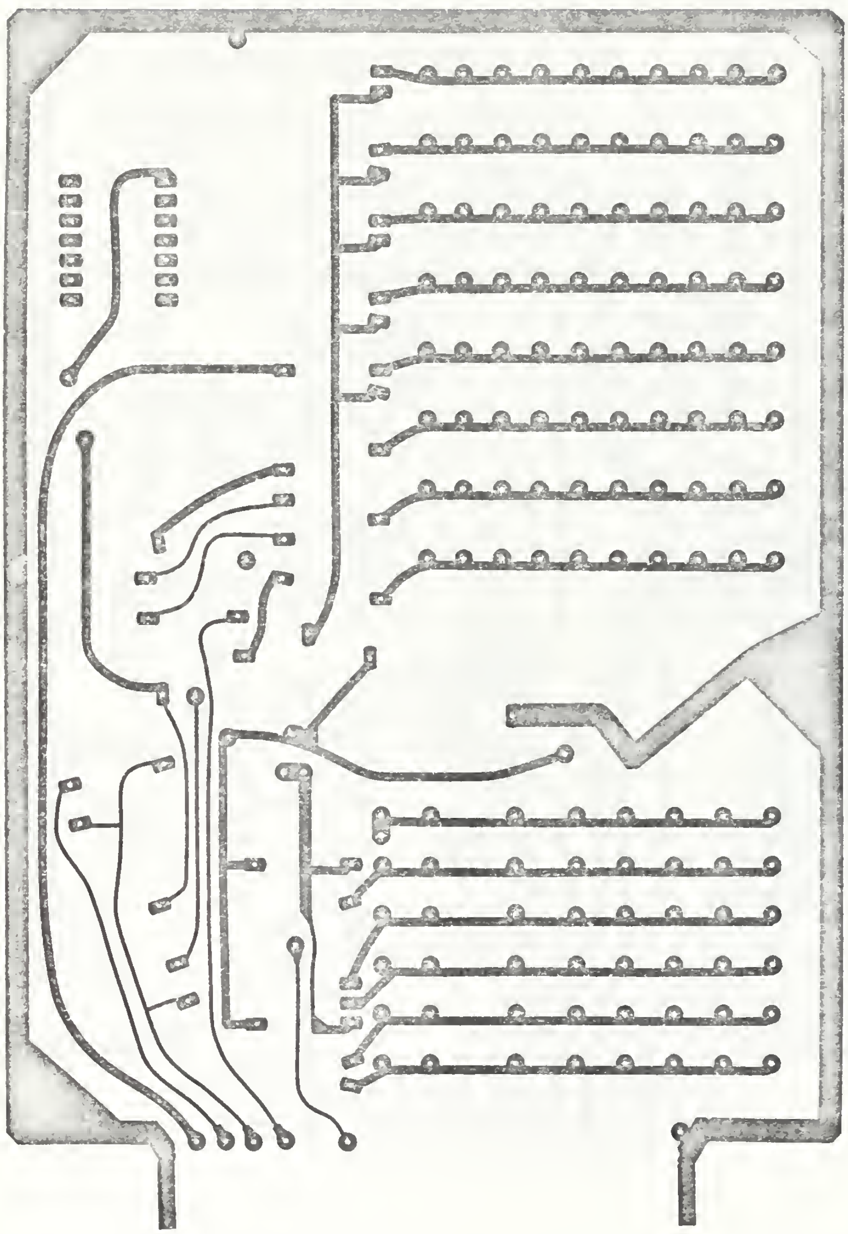


Figure 31. Top Foil of Transmitter Coding Board.

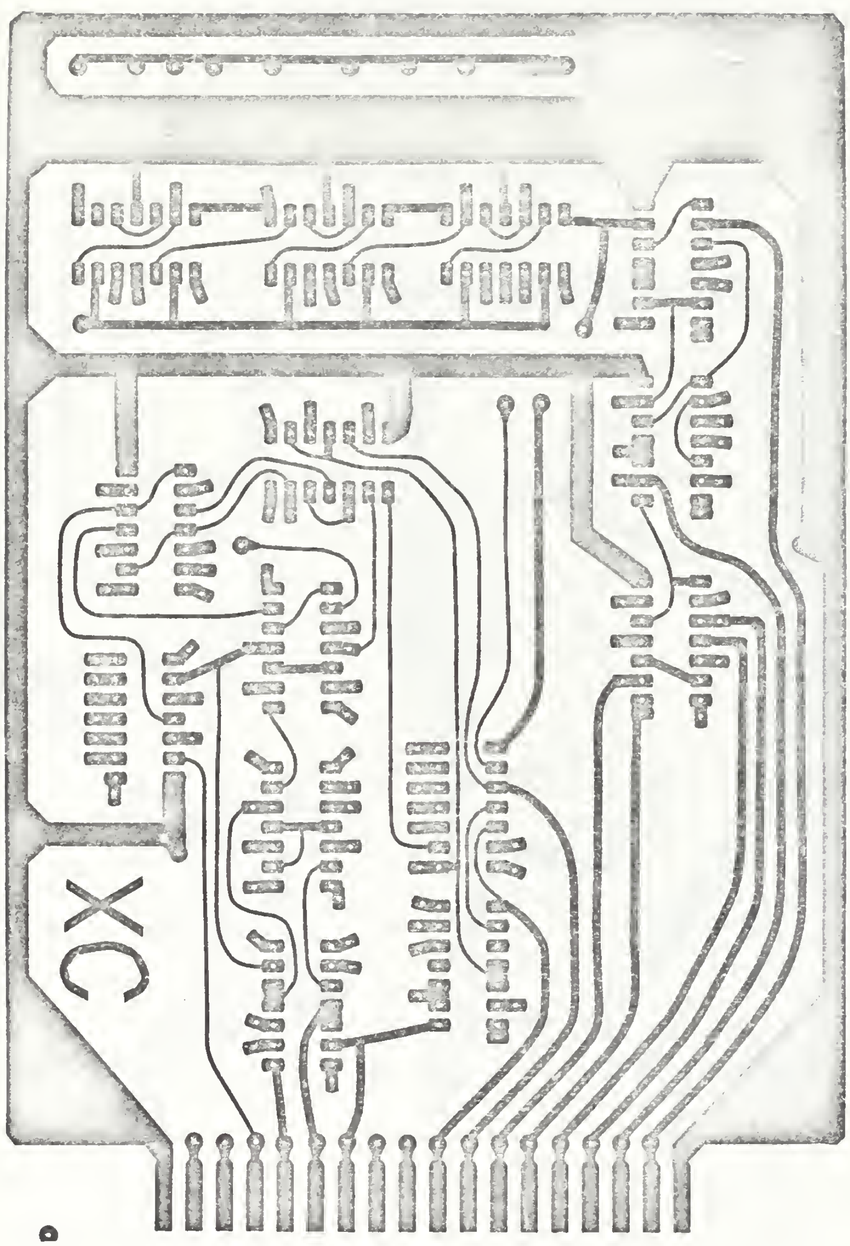


Figure 32. Bottom Foil of Transmitter Control Board.

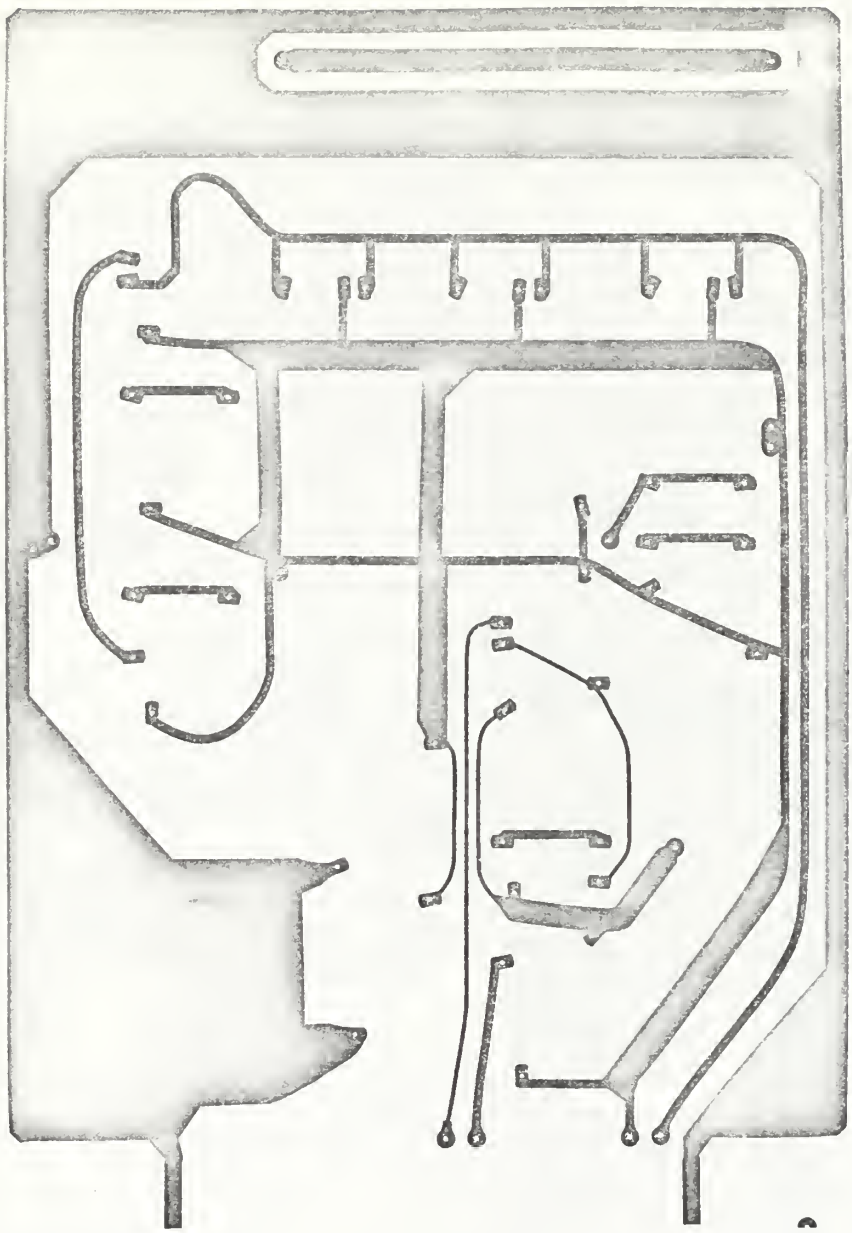


Figure 33. Top Foil of Transmitter Control Board.

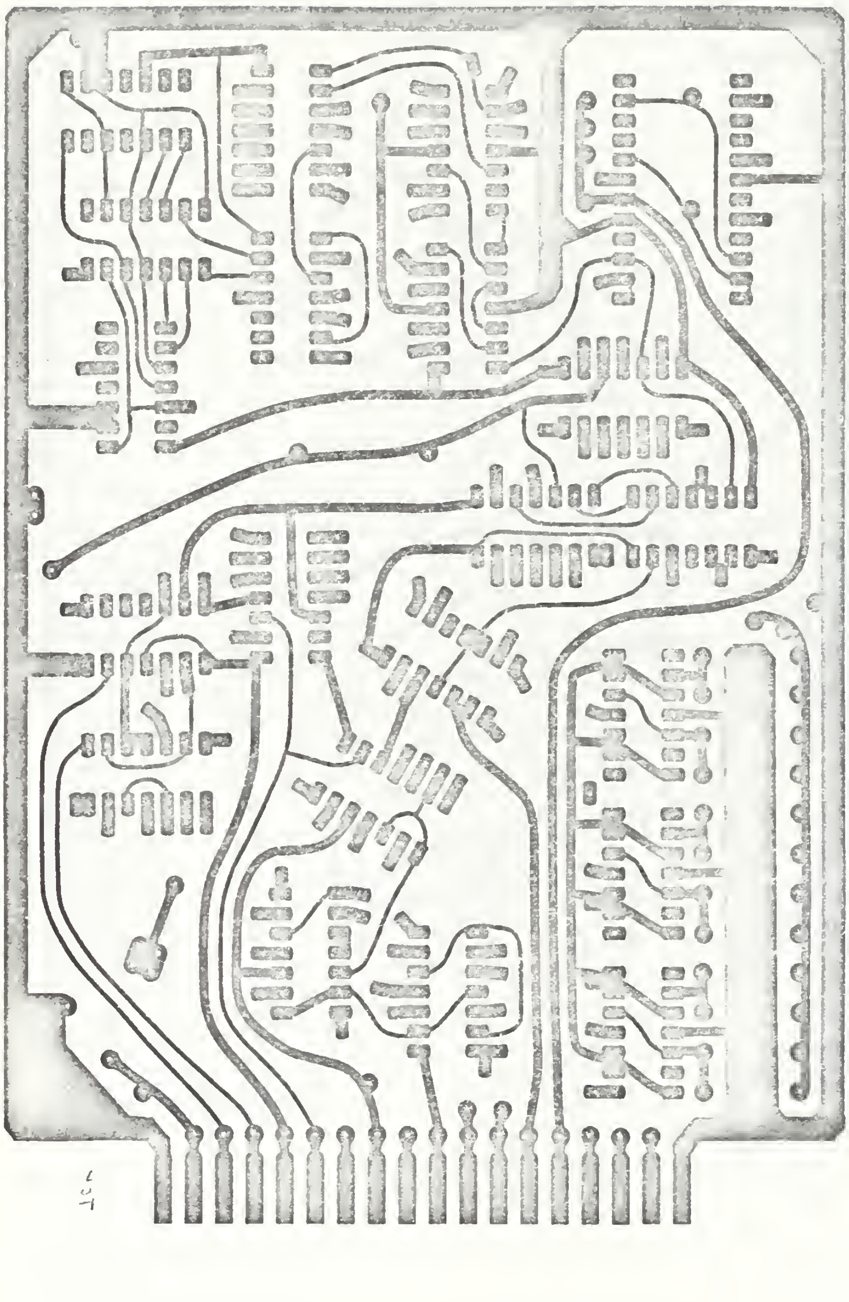


Figure 34. Bottom Foil of Control & Storage Board.

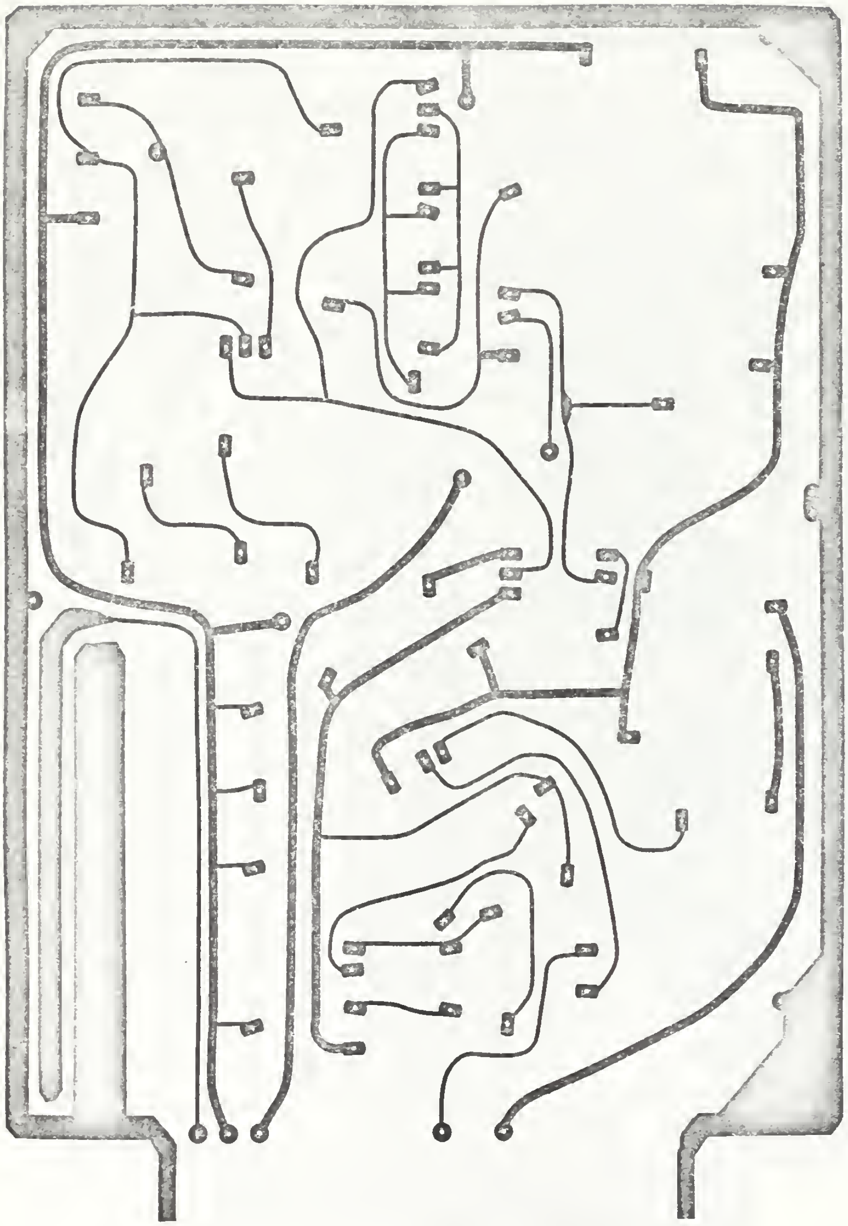


Figure 35. Top Foil of Control & Storage Board.

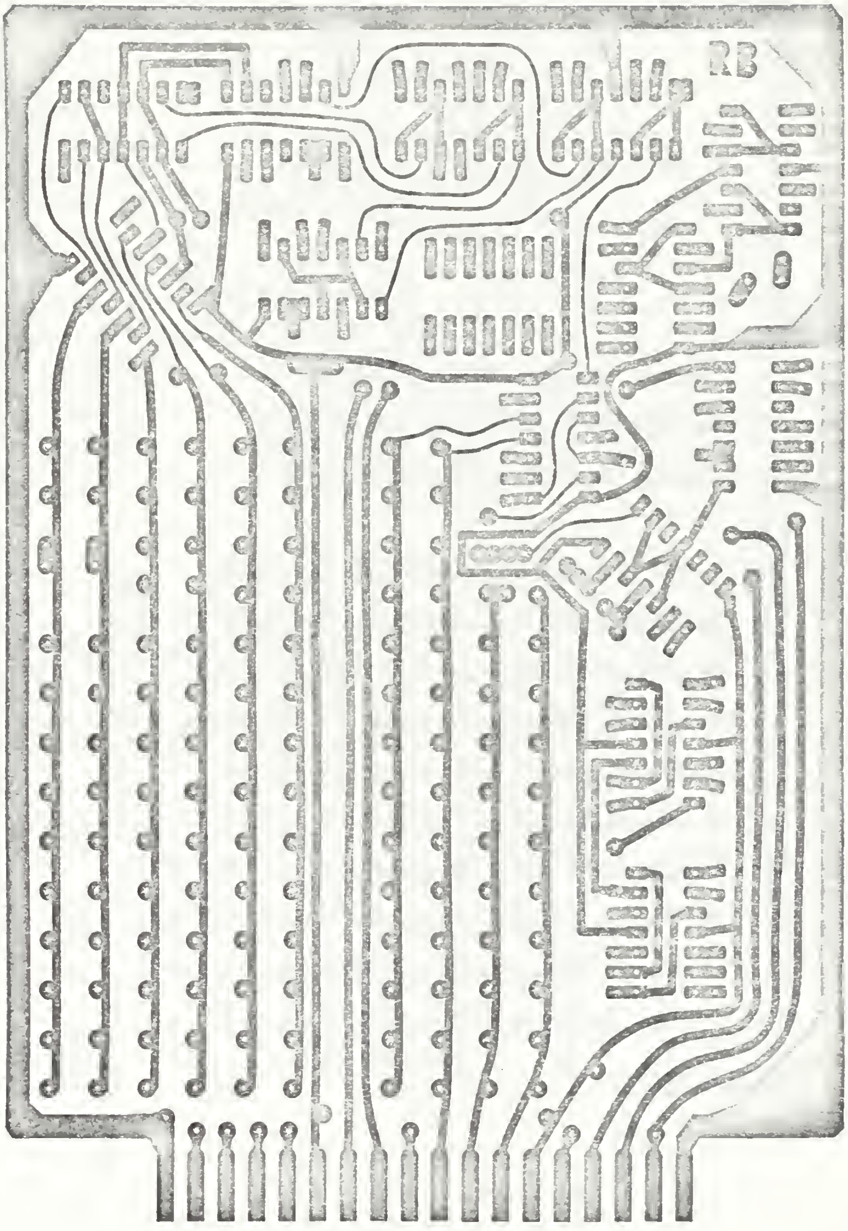


Figure 36. Bottom Foil of Receiver Decoder Board.

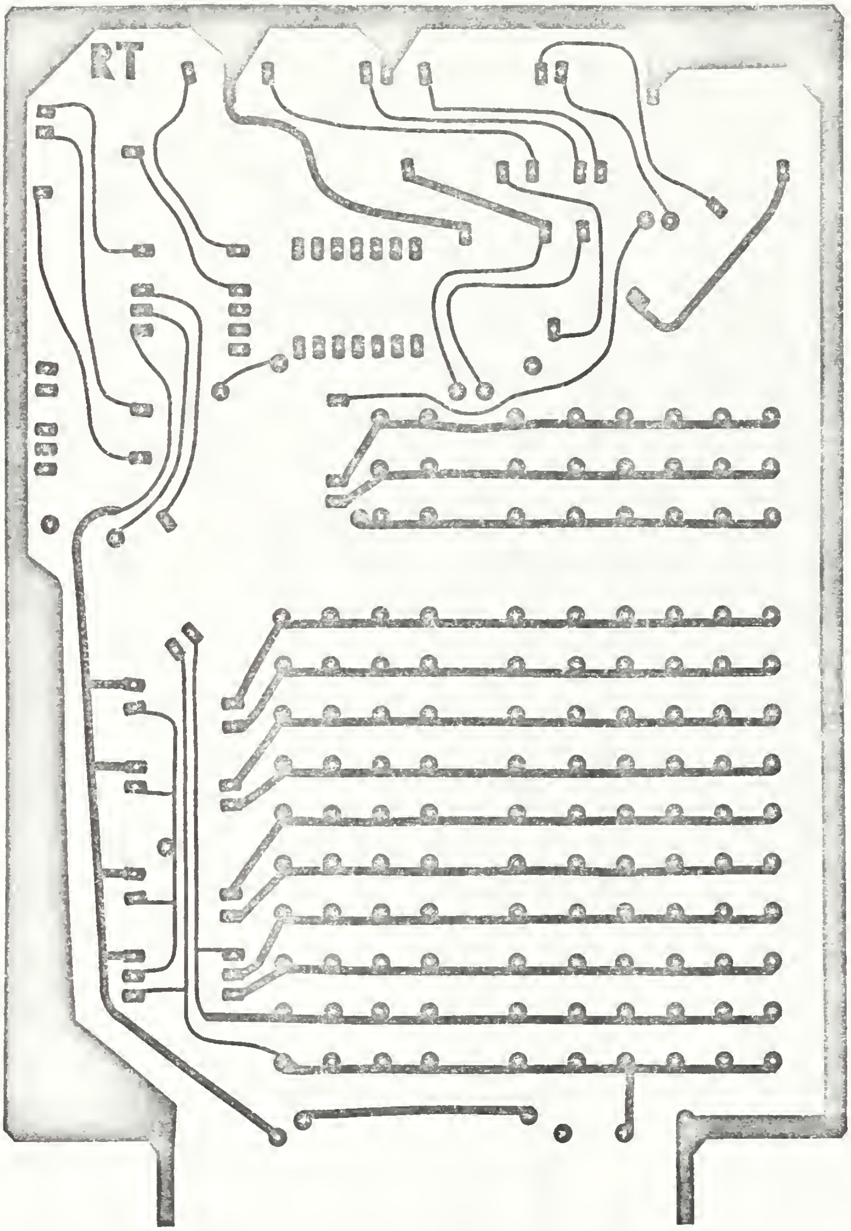


Figure 37. Top Foil of Receiver Decoder Board.

CROSS CONNECT SHEET

CONNECTIONS COMMON TO BOTH THE TRANSMITTER AND THE RECEIVER

PURPOSE	NAME	CC	TC	XC	TS	CS	RB	OUTSIDE
3 KHz limited information	XMT			*XMT		13		FILTERED
Ground	GND	1,18	1,18	1	1,18	1,18	1,18	CAMERA 4
TTL Vcc supply	+5V	5	13	16	13	3	6	*PWR SUPPLY
Storage supply	-12V				4	5		*PWR SUPPLY
4800 Kz Sq wave osc	SLO OSC	*9	5	17		14		
400 KHz osc	FAST OSC	*13		6		10	12	

* Source

CROSS CONNECT SHEET

CONNECTIONS TOTALLY WITHIN THE TRANSMITTER

PURPOSE	NAME	CC	TC	XC	TS	OUTSIDE	CAMERA
Pos sup for diff amp	+15V	8					*1,3,10
Vertical sweep	VERT	*7					2
Horizontal sweep	HORIZ	*6					9
Video input	VIDEO	17					*Output
Neg sup for diff amp	-6V	16				*PS Drop	
Storage clock (fast & slow)	T			*5	15		
Count of "T" inverse	-128			14	*12		
Tally result	4			9	*9		
Tally result	32			8	*10		
Inv. trigger order	-TRIG	4	11	*13	11		
Inv. sequential order	-SEQN		12	*4			
Sequential mode	SEQN			*12	3		
Code mode	CODE			*18	6		
Change from prediction	ONE		4		*7		

(Continued On The Next Page)

CROSS CONNECT SHEET

CONNECTIONS TOTALLY WITHIN THE TRANSMITTER (continued)

PURPOSE	NAME	CC	TC	XC	TS
Code the Run-Length	RLC		*3	10	
Coded data output	DATA		*2	2	
Inv. sequential output	-OUT			11	*2
Load new line	LOAD			*7	8
Make tally decide mode	GO		*6	3	
Run-Length count	COUNT		7	*15	
Half clock	T/2	13			*17
Digital video info	A/D	*11			5

CROSS CONNECT SHEET

CONNECTIONS TOTALLY WITHIN THE RECEIVER

PURPOSE	NAME	CS	RB	OUTSIDE
Pwr to drive scope video	+12V	8		*Pwr Supply
Receiver code mode clock	Slo Clk	*16	3	
Receiver code mode signal	Signal	*12	16	
Scope vertical drive	Vert	*2		Scope Vert
Count so many bits & change	Change	4	*15	
If N is ordered stop change	"N"	7	*9	
Negative trig for horiz sweep	Scope	*11		Scope Trig
Decoded trigger order	Trig	9	*8	
Decoded sequential order	Seqn	15	*7	
Come to run length-locks up	Fast Run	6	*11	
Modulates scope control grid	Video	*17		Scope Inten

Figure 38. Four Completed Circuit Boards

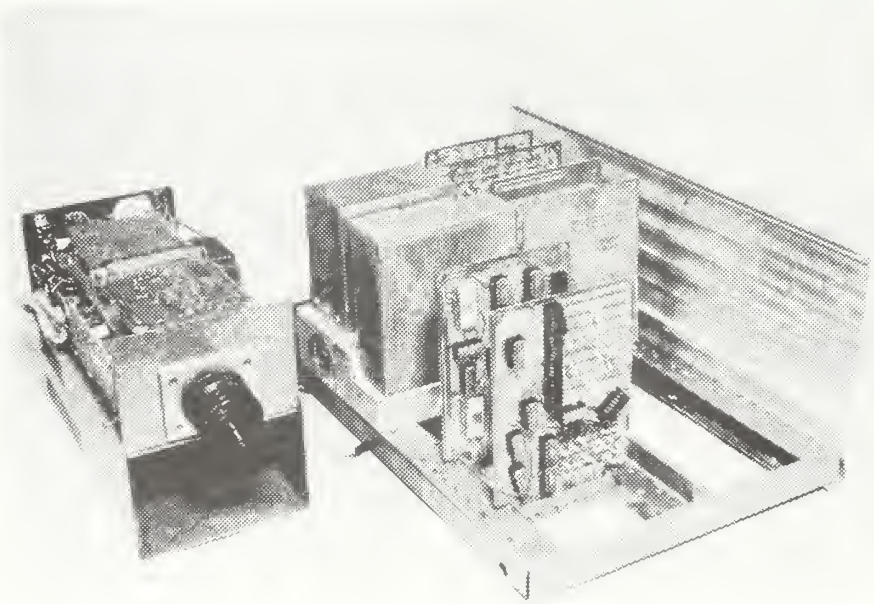


Figure 39. The Assembled Television System

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Voiceband Television

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A need exists to send television on channels of limited bandwidth, particularly 3 kHz. Successive images must have adequate picture content yet be frequent enough to give the appearance of motion. A new coding scheme was devised to meet this need for video data compression.

A 2400 baud system was designed and built. A hierarchy of transmission modes is used which allows the transmitter to choose

20.
the most efficient of 3 modes to send a line. One mode uses a variable-length Instantaneously Uniquely Decipherable code optimized for the statistics of some typical expected pictures. The picture size is 64 by 64 elements, each with 4 luminance levels. The transmitter has a stored line (129 bits) and a two-dimension model to predict the following line. After comparing the prediction to a fresh line the deviations from the prediction are sent. Then the receiver uses the same model to update a similar stored line to be displayed. Frame duration can range from .13 to 3.54 seconds as determined by the actual picture.

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c.1 A practical voiceband
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